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ASTROPHYSICS DATA OPERATIONS

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the Astrophysics Division, NASA Headquarters.

APRIL 15, 1986

PREFACE

The forthcoming launch of the Hubble Space Telescope (HST), together with plans to initiate development of the Advanced X-Ray Astrophysics Facility (AXAF) and the Space Infrared Telescope Facility (SIRTF), herald an era of increased importance and cost for long-term, multi-observatory operations. These considerations led the Astrophysics Program Office at NASA Headquarters to request a review of the options and opportunities available for future Astrophysics mission operations.

This report on Astrophysics Data Operations, commissioned through the Goddard Space Flight Center, reflects the views of a great many informed participants, including NASA and non-NASA personnel experienced in the operation of past and current missions, members of the AXAF and SIRTF project teams, and non-NASA scientists with an interest in this important area. The study thus provided an exceptional opportunity to unite scientific objectives, technical requirements, management needs, and fiscal and political constraints into a cohesive set of recommendations that reflect both direct experience with past programs and a strong commitment to future ones.

The report contains a number of conclusions, suggestions, and recommendations that are best introduced in the following contexts:

(1) Precedents for long-term NASA mission operations;

(2) Unique aspects of HST performance and operations;

(3) Importance of understanding HST drivers of complexity and cost;

(4) Central role of Mission Operations and Data Analysis (MO&DA) in future missions; and

(5) Need for immediate AXAF and SIRTF program decisions.

(1) First of all, <u>there are important precedents for the extended operation of NASA space missions</u>. It is often said that HST and the other "Great Observatories" will be the first long-term space-astronomy missions, and indeed HST is the first to be planned for extended operation with Space Shuttle servicing. In fact, however, NASA has been supporting long-term mission operations for at least a decade. Examples include the Orbiting Astronomical Observatory (OAO), the International Ultraviolet Explorer (IUE), the Solar Maximum Mission (SMM), the Atmospheric Explorer (AE), the International Sun-Earth Explorers (ISEE), the Dynamics Explorer (DE), and the Pioneer and Voyager missions. It is true that none of these were funded and developed as long-term projects. To the contrary; many were repeatedly threatened with cancellation. The fact that they were continued is a tribute to the scientific and technical creativity of those involved with these programs and to the commitment of NASA and the government generally to continued support of productive research satellites. Moreover, the long-term success of NASA projects in other program areas shows that the growing cost of the operations phase is more than simply an Astrophysics

Division concern. We have moved into an era in which a broad NASA commitment to continuing mission operations will play a vital and integral role in the national research and development program as a whole.

(2) On the other hand, the HST project is itself unique and unprecedented in several respects. No other Astrophysics mission begins to approach HST in the range of technical capabilities to be provided or in the complexity of its operation. Furthermore, no other mission has carried such high expectations of operational performance, particularly in the provision of extensive data-handling capabilities from the moment of launch onwards. These comparisons apply not only to past missions but also to future projects such as AXAF and SIRTF. It is therefore irrelevant and misleading to compare the projected costs of AXAF and SIRTF with those of HST, since such a cost comparison is certain to show an illusory "cost savings." The projected costs of AXAF and SIRTF should be evaluated independently. There remain numbers of opportunities to make significant AXAF and SIRTF cost tradeoffs and management decisions to ensure that scientific productivity is high and the associated cost reasonable. This report suggests areas that can be pursued. Thorough reviews of each project and prompt management decisions prior to project approval are required.

(3) Precisely because HST is so challenging, and expectations of its performance so high, we should continue to seek a greater understanding of HST drivers of complexity and cost. Clearly, however, HST "is what it is"--the most ambitious Earth-orbital scientific mission ever developed by NASA. Projects can always be constrained to reduce cost, but with HST launch planned for 1987 such an approach would be penny-wise and pound-foolish. Given the high expectations for HST operational performance, no near-term effort to save costs makes sense. Instead, every effort should now be made to ensure that HST becomes successfully operational on time and within budget. On the other hand, the HST project team and the staff of the Space Telescope Science Institute (STScI) may be expected to benefit from actual experience with HST operations in the months and years following launch. With such experience to guide them, HST project personnel should then find new ways to reduce the complexity of operations, increase scientific productivity, and reduce cost.

(4) More generally, we must now accept this reality: Mission Operations and Data Analysis will occupy a central role in virtually all future space missions. The need to commit substantial resources to the collection, distribution, analysis, and archiving of scientific data is already with us. In some areas, as the enclosed report points out, cost savings may be achieved through common efforts and through shared experience and resources. In the main, however, the report's recommendations seek to ensure that the major investments we plan to make in the development of future space observatories will be protected through commensurate planning for effective data handling and analysis. Both the astronomical community and NASA are already taking positive steps in this area. Enlightened leadership, stable support, and deliberate encouragement can lead to significant improvements in data-handling capabilities at little or no additional cost.

(5) Finally, it is important to stress that program decisions for AXAF and SIRTF must be made now. It is vital that the institutional arrangements for the MO&DA phase of AXAF and SIRTF be decided in the near future. While there is a spectrum of strong opinions about which approach is best--for example, a single institute for the Great Observatories, separate institutes, NASA centers, or various hybrid organizations--there is general agreement about the functions that such a supporting organization must perform. First of all, any organization chosen or constructed to support AXAF or SIRTF MO&DA functions must undertake to ensure the scientific integrity and productivity of the mission as part of its responsibility to the broader scientific community. In addition, such an organization must be an integral, active part of the NASA project team and consequently responsible and accountable to NASA in a management sense. NASA Headquarters should review and compare the options available to each project in consultation with the NASA centers concerned and the science advisory structure as part of a systematic procedure to select an advantageous approach for each project. The potential for major cost avoidance and savings offered by a rapid decision appears to outweigh putative cost differences among competing approaches. We should remember that many institutional arrangements can be made to work effectively, provided they are responsive to both the scientific community and to NASA, are an integral part of the NASA project team, and have clear roles and responsibilities.

In view of the above points, the Study Group decided it was not appropriate to try to identify a specific "cost savings" associated with each recommendation. Instead, the report reflects the strong belief that NASA, its project teams, and the astronomical community can work together, taking advantage of shared facilities, existing capabilities, and a wealth of experienced personnel to learn from the past. In this way, we can build trust, increase scientific productivity--and contain costs.

This report would not have been possible without the active participation of the many scientists, engineers and managers who took the time to contribute their views and experience. A special thanks is due Albert Opp, Richard Harms, Paul Blanchard, and Sharon Smith. This study was supported through a contract with Applied Research Corporation.

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INTRODUCTION

Background. In March 1985, the Director of Astrophysics, NASA Headquarters, requested a study of the operation of future Astrophysics missions. This request grew from a recognition of the increasing importance of the Mission Operations and Data Analysis (MO&DA) phase of such projects. In the context of this study, MO&DA is taken to include those on-orbit and ground operations and functions necessary to collect photons in space and provide the resulting data to the scientific community for analysis and publication.

Annual expenditures for MO&DA have, in the past, been modest compared with typical annual development costs and have represented only a small fraction of the NASA Research and Development (R&D) budget. Consider, for example, the High Energy Astronomical Satellite-2 (HEAO-2), the International Ultraviolet Explorer (IUE), the Solar Maximum Mission (SMM), and the Infrared Astronomy Satellite (IRAS), all of which continue to receive support for data analysis and dissemination. In fiscal year 1985 dollars, the commitment of NASA R&D funds for the MO&DA phase for all four missions combined amounted to a "steady state" level of approximately $31M.

By comparison, the projected "steady state" MO&DA budget for the Hubble Space Telescope (HST) is approximately $70M in FY85 dollars. This is exclusive of the cost for next-generation instruments and for spacecraft maintenance and refurbishment. Moreover, HST is planned to be only the first of a series of long-lived "Great Observatories" in space. In addition to HST, it is expected that the Gamma Ray Observatory (GRO), and new-start candidates Advanced X-Ray Astrophysics Facility (AXAF) and Space Infrared Telescope Facility (SIRTF), will all be in operation by the turn of the century.

These considerations raise a number of questions, some of which carry important implications for the NASA budget:

- Are future "Great Observatories" likely to have annual MO&DA costs similar to that of HST?

- Do AXAF and SIRTF, in particular, resemble X-ray and infrared versions of HST, or do they more resemble their simpler scientific precursors, HEAO-2 and IRAS?

- What have we learned from the past? For example, are there economies of scale or benefits from the use of common project elements? How can we maintain the quality of science at reasonable cost?

- How can we ensure a cost-effective yet scientifically productive approach to data handling and archiving during the Great Observatory era?

- How should NASA and the scientific community exploit the synergism of simultaneous observations from the Great Observatories? In the face of constrained budgets, can they work together to ensure the continued exploration of the Universe through use of multispectral observations?

Charge: In order to address these questions, together with associated concerns and perceptions, the study participants were requested to:

1. Analyze operations and data distribution for astrophysics missions as an integrated program across all major missions planned for launch before the turn of the century.

2. Examine the processing and distribution of data to enhance "problem-oriented" analysis of multispectral data from various missions at remote sites.

3. Consider any beneficial role or use of existing or planned infrastructure, in particular the Space Station, the National Space Science Data Center (NSSDC), the Tracking and Data Relay Satellite System (TDRSS), and the Space Telescope Science Institute (STScI).

The study was expected to produce a report that had benefited from discussion and comment by the general scientific community.

Conduct of the study. The study was conducted in three phases. Phase I consisted of a Data Management Workshop held 17-19 April 1985 at Goddard Space Flight Center (GSFC), with attendance limited to NASA personnel experienced primarily in Astrophysics Mission Operations and Data Analysis (see Appendix A). This workshop reviewed the operations of such past missions as the Orbiting Astronomical Observatory (OAO) series, IUE, and IRAS; missions in progress, including the Cosmic Background Explorer (COBE), GRO, and HST; and plans for Solar Optical Telescope (SOT), AXAF, and SIRTF. Project experience from other areas was also discussed, particularly the Atmospheric Explorer/Dynamics Explorer (AE/DE), the International Solar-Terrestrial Program (ISTP), and the Upper Atmosphere Research Satellite (UARS). In addition, presentations were received from the National Science Foundation (NSF), the NSSDC, and representatives of the planetary program. The primary purpose of Phase I was to review as much relevant experience as possible, so that a focused set of discussion topics and a workable agenda could be developed for Phase II.

NASA has conducted the development and operation of its Astrophysics missions in a wide variety of ways. During Phase I of the present study, the Study Group sought to identify common elements or approaches to mission-operations functions within apparently dissimilar projects. The accompanying Figure 1, "Mission Operations Functions (Historical Pattern)," shows those elements that appear to be common to the operation and data flow of all Astrophysics missions that have been flown or planned so far. In this figure, each element within a rectangle represents a particular function; solid arrows show the flow of a product from one function to another; and dashed arrows represent two-way interactions, such as coordination or joint planning. Because of interaction and feedback, planning for data handling and dissemination exerts an influence on other program functions and products even at early mission stages. The centrality of the onboard data collection and processing function symbolizes the fact that this function helps to determine all functions around the periphery of the diagram. The figure helped the Study Group to consider the various missions discussed in Phase II from a unified point of view. In the future, of course, technological or management innovation may lead to a diagram with different topology.

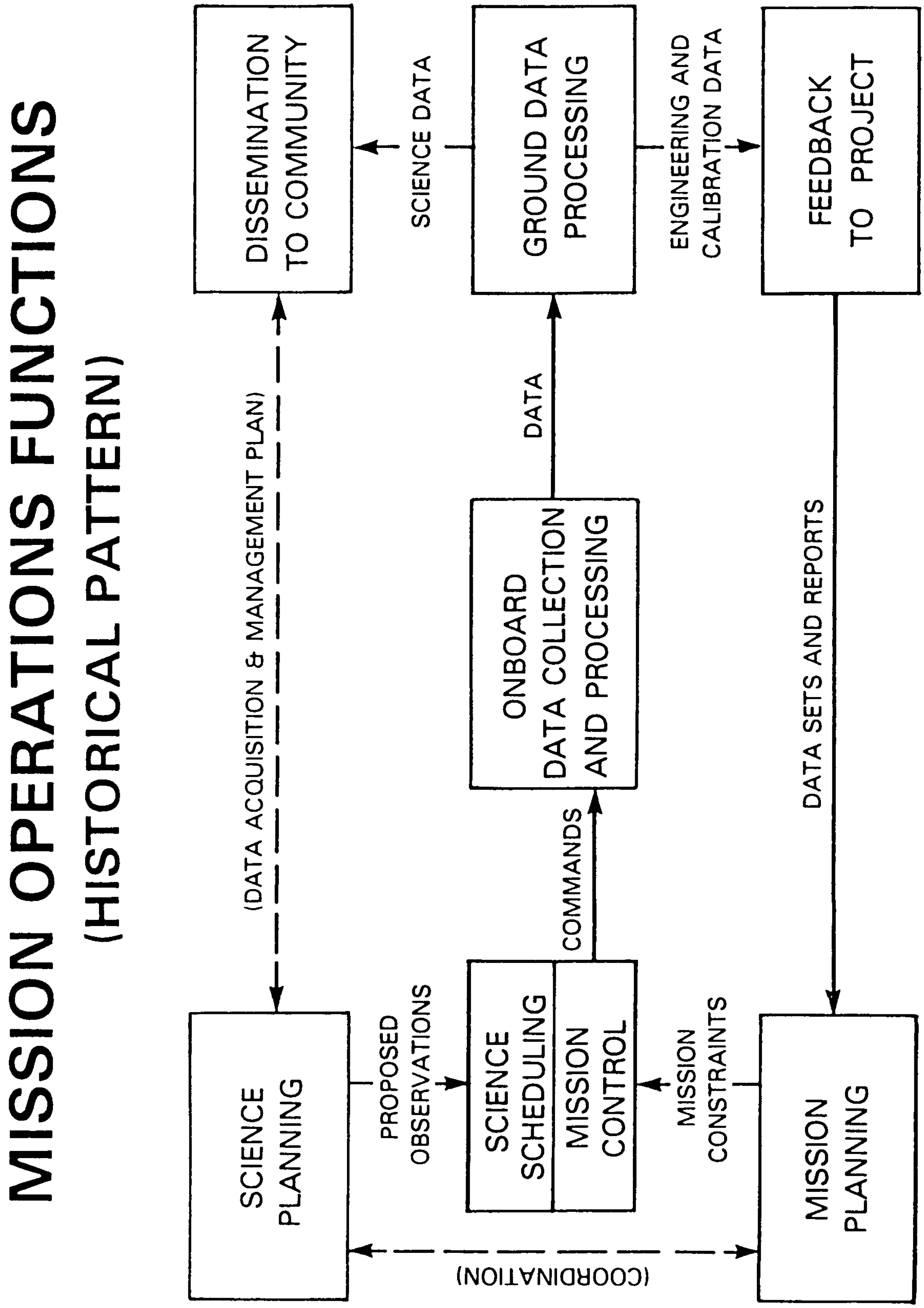
MISSION OPERATIONS FUNCTIONS
(HISTORICAL PATTERN)
SCIENCE PLANNING
(DATA ACQUISITION & MANAGEMENT PLAN)
DISSEMINATION TO COMMUNITY
PROPOSED OBSERVATIONS
SCIENCE SCHEDULING
MISSION CONTROL
COMMANDS
ONBOARD DATA COLLECTION AND PROCESSING
DATA
GROUND DATA PROCESSING
SCIENCE DATA
ENGINEERING AND CALIBRATION DATA
FEEDBACK TO PROJECT
DATA SETS AND REPORTS
MISSION CONSTRAINTS
MISSION PLANNING
(COORDINATION)

FIGURE 1

Phase II consisted of a workshop held 17-19 September 1985, also at GSFC, involving some of the participants from Phase I together with participants from the external research community (see Appendix B). This workshop considered the data recommendations of the National Academy of Sciences' Astronomy Survey Committee and Committee on Data Management and Computation (CODMAC), the experience of the planetary community, the activity of NSF, and the plans of the Academy's Committee on Space Astronomy and Astrophysics (CSAA) for a more extensive study of similar and related topics. The experience of the IUE, IRAS, HEAO-2, and HST projects was discussed in detail; there followed a consideration of plans for future missions that focused on AXAF and SIRTF. Among the main topics emphasized were mission characteristics and complexity of operations, centralized versus distributed data handling and archiving, multimission operations centers, standardization of data formats, and data-analysis requirements. The plans and potential roles of Space Station, TDRSS, and NSSDC were also reviewed and discussed.

Phase II produced a set of conclusions and recommendations, set forth in a draft report of 30 January 1986 that served as the basis for the final Phase III solicitation of comments from the general scientific community. An address on the Phase II status of the present study was presented to a public-policy session at a meeting of the American Astronomical Society on 6 January 1986. The draft report was also sent to a large number of institutions and individuals for comment. In addition, the status of the study was discussed with the responsible NASA advisory panels prior to publication of the final report.

The conclusions and recommendations presented here are those of the Phase II Study Group, which is listed below:

BERNSTEIN, Ralph	IBM Corporation
BLANCHARD, Paul	Applied Research Corporation
BOGGESS, Albert	Goddard Space Flight Center
BOYCE, Peter	American Astronomical Society
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HARMS, Richard	Applied Research Corporation
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MEAD, Jaylee	Goddard Space Flight Center
OPP, Albert	Goddard Space Flight Center
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PHASE II CONCLUSIONS AND RECOMMENDATIONS

The most fundamental finding of this study is that the application of basic management principles is vital to scientifically productive and cost effective operation of future space-astronomy missions in the MO&DA phase.

The effectiveness of mission operations is deeply rooted in the decisions made during the definition and development phases of the project. This finding is in agreement with the earlier CODMAC conclusion that it is management and organizational issues, rather than technological issues, that form the most significant potential barriers to successful mission development, operations, data processing, and distribution of data to the scientific community.

We first describe the general conclusions and recommendations of the study, followed by discussion in each case. There are four of these, appearing under the headings:

A. Institutional setting and early involvement of the science and operations team;

B. Management simplicity and adequate staffing;

C. Communication among projects; and

D. Data archiving.

We then return to the charge to the Study Group and comment upon each of its elements in the light of the workshop findings, adding relevant information. The present section concludes with a more detailed list of suggestions that cover the planning of data handling and archiving.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

A. Institutional Setting and Early Involvement of the Science and Operations Team

Conclusion: When measured against their expectations for scientific productivity and cost-effective operation in the MO&DA phase, the HEAO-2, IUE, and IRAS missions must be considered outstanding successes. This operational success is due primarily to three factors:

1. An early choice of institutional setting for operations, which established clear lines of scientific and management responsibility and ensured organizational continuity.

2. An early and continuous involvement of scientific and operations personnel in mission definition, development, and implementation.

3. A strong sense of responsibility by those involved to both NASA management and the astronomical community.

Recommendation: The choice of an institutional setting for both AXAF and SIRTF operations should be made in the near future; the scientific and operations teams that will carry out these missions should be defined as early as possible and be given responsibility for mission operations success from that point onwards. Team members should have a personal stake in the success of the project, and NASA should make it clear how these arrangements will ensure management responsibility, scientific excellence, and oversight by the scientific community. In general, these arrangements should be in place at the time of project definition (Phase B) and validated together with the rest of the project prior to the development phase (Phase C/D).

Discussion: NASA must now examine future institutional arrangements for AXAF and SIRTF. Of past programs and those currently under development, only IUE and HST were initiated as observatories intended from the beginning for substantial use by general observers. HEAO-2 was developed as a Principal Investigator (PI) facility. The IRAS mission, designed to provide an all-sky survey for the research community, was carried out by a Science Working Group with a team leader. However, because IRAS and HEAO-2 satisfied the three criteria listed above, they both proved to be highly productive and accessible to the general research community as well. (A description of each of these missions is contained in the later section entitled Existing Information Base for Study.) The success of these past programs shows that a variety of organizational approaches can support the science operations and the associated team--NASA centers, universities, industry, project-specific institutions, and combinations of these have all been successful. Success is most strongly correlated with early identification of the location and structure for a committed science and operations team. This institutional setting for the long-term operation of the project promotes effective participation in the program, ensures the scientific integrity of the mission, and ensures preservation of an "institutional memory" throughout.

The Study Group recognized the need to define clear institutional and organizational structure as urgent tasks for the AXAF and SIRTF projects. Such arrangements must take into account that each of these facilities is intended for use not just by the PI's but also the general research community. Each project has a baseline concept, but neither yet has a formally approved organization. Numbers of alternatives are still under consideration. The astronomical community and NASA must tegether come to terms with, and accept responsibility for, the long-term arrangements for these major space observatories if they are to be operated cost-effectively.

Furthermore, there must be a clear end-to-end integration of responsibilities that properly reflects the cultures and capability of all institutional elements. Early involvement of the scientific, engineering, and operations teams is essential for cost-effective and scientifically productive operation in the later MO&DA phase. Several factors impede this desirable integration of a team effort: the politics of selling a large program, the long timescales involved, the tendency to focus attention and resources on immediate technical problems, and the perceived and real desires of NASA and the astronomical community.

This last factor can be a major impediment when discussions and debates over important concepts such as "responsibility", "control," and "independence" lead to conflict, artificial barriers, adversarial relations, and, even worse, delayed decisions that can be detrimental to cost, schedule, and mission success. Consequently, the Study Group concluded that such a systems approach including early involvement is imperative if the users are to accept responsibility for, and become involved in, cost control of major programs. Even though there are many other contributing factors, such as lack of continuity of key personnel at all levels, the Study Group believed that much of the HST cost growth could have been avoided if the institutional setting, including scientific and management responsibility and associated personnel, had been identified for the operational phase and put into place earlier in the program.

The above conclusions have major implications for AXAF and SIRTF. These projects are intrinsically less complex than HST and thus present opportunities to avoid cost growth through prompt management initiatives. For example, the total manpower associated with mission operations for HST (exclusive of science investigators and data analysis) is just over 500 man-years per year, which is similar to manpower levels for planetary MO&DA during past major planetary encounters. By contrast, missions such as HEAO-2, IUE, and IRAS require only on the order of 50 to 150 man-years per year each for the same functions. The differences can be attributed directly to the large number of management interfaces, instrumental complexity, complex operation modes, and intricate scheduling procedures for HST.

In addition, neither AXAF nor SIRTF envisions real-time operations, a major cost driver for missions in low-Earth orbit. Pointing requirements are less stringent by an order of magnitude than for HST, and (unlike HST) only one instrument will operate at a time. The data rates are lower as well, and the number of operation modes is far fewer than for HST. In addition, each of these missions has been preceded by a relevant "prototype:" HEAO-2 in the case of AXAF, and IRAS in the case of SIRTF. These prototypes have provided a valuable base of documented experience on which to build MO&DA plans for the future missions.

Present AXAF specifications call for a space observatory that, in many respects, resembles a larger version of HEAO-2 rather than an X-ray version of HST. The Study Group concluded that there is a good chance that MO&DA costs for AXAF can be held much below those of HST if the foregoing management recommendations are implemented. Although SIRTF operations are not as well defined as those of AXAF, a similar conclusion should apply to SIRTF once more programmatic detail and associated cost estimates are available. However, careful attention must be paid to past missions, since it is not clear that HST took full advantage of the experience gained on IUE and OAO.

While good management is essential to take fiscal advantage of these technical differences, the Study Group concluded that, to a first approximation--even if nothing is done beyond the actions now planned by the AXAF and SIRTF projects--the MO&DA cost for each of these missions should be significantly less than that of HST because of relative technical simplicity alone. However, the Study Group also examined a number of ways in which the program costs of AXAF and SIRTF might be lowered through standardization or commonality of various program elements.

The AXAF project has already baselined the multimission support facility at GSFC for spacecraft operations, taking advantage of existing facilities and reducing cost. The SIRTF project is considering a similar option. The use of common science or operations control centers beyond this does not appear feasible. Large central organizations appear to offer no obvious efficiencies of scale. Data formats are already becoming standardized through the systematic efforts of major research centers and the grass-roots support of individual scientific groups. The sharing of hardware is counterproductive, since it quickly becomes obsolete and expensive to service.

Software offers the best possibility for cost savings. It is possible that substantial portions of the sophisticated HST software (e.g., that for ground support or for data archiving and distribution) can be used by AXAF and SIRTF. While such savings could be significant in absolute dollars, and consequently important to pursue in some cases, the Study Group felt they are unlikely to represent a substantial fraction of the MO&DA or development budgets of either AXAF or SIRTF.

B. Management Simplicity and Adequate Staffing

Conclusion: Complex management schemes, particularly the involvement of several NASA centers, and complicated contractor arrangements have in the past worked to the detriment of missions such as HST and IRAS. Moreover, the size of the science and operations team's staff has often been too small to ensure that cost tradeoffs made during the development phase will promote simplicity and scientific productivity during the MO&DA phase, especially in the cases of the major missions.

Recommendation: NASA should maintain streamlined organizations for AXAF and SIRTF, minimizing major multiorganizational involvement in project management, and should staff the science and operations team adequately.

Discussion: With regard to management simplicity, it may be said that no rule is so obvious, important, and widely ignored. Every pressure of the sociology of a large organization works against keeping things simple. Nevertheless, NASA must take a careful look at management arrangements that apportion scientific and programmatic responsibilities among different entities, such as NASA centers. If the management plan calls for a second organization to take over project management from the first, the second organization must be involved with the project from the beginning. Roles and responsibilities must be clear, and the project must make sense as a management system. NASA should, in effect, "systems engineer" the institutional arrangements for the Great Observatories.

An adequately sized and technically competent scientific and operations staff (involving both NASA and non-NASA personnel) is also important to project success. The most successful projects recognize that key scientists and operations personnel experienced in flight projects can form an effective nucleus of technical advisors that can contribute materially to "systems engineering"--particularly early in the project, when much conceptual design must be done. However, even during the fabrication and operational phases of the project, experienced scientists (whose personal success depends on the success of the program) and their support staff form an excellent cadre that can help maintain the quality of the mission and ensure that optimum cost tradeoffs are made. In the past, some difficulties have arisen through the inability of the science teams to be "everywhere at once" and to be kept fully informed on technical matters when they lacked the funding for staff. Again, the Study Group did not believe that one institutional setting is more important than another in nurturing this core scientific expertise--as emphasized earlier, NASA centers, universities, industry, and institutes all can be successful. However, the group did conclude that a core of key scientists and operations personnel, and the associated feeling of scientific responsibility, are vital to the early avoidance of costly design and development problems and to the ensuring of later cost-effective operations.

C. Communication Among Projects

Conclusion: Communication among past NASA Astrophysics projects has been surprisingly limited, with relatively little sharing of mission experiences.

Recommendation: NASA should implement a mechanism for regular and intimate interactions among teams from the major space-observatory programs. In particular, NASA should seek a means to ensure that experience from programs such as IUE, HEAO-2, IRAS and HST is shared with the new AXAF and SIRTF program teams.

Discussion: The study group found a rich reservoir of experience available among participants in the many missions reviewed. A striking feature of the study, highlighted during Phase I, was the remarkable degree to which the different Astrophysics mission groups are unaware of one another's experiences. Several participants in both Phase I and Phase II remarked that the educational benefit of hearing a variety of presentations on similar programs was one of the major surprises and rewards of the study for them. This observation points up a clear opportunity to aid future programs by establishing a mechanism to ensure such communication, particularly to the benefit of the AXAF and SIRTF missions. We note, however, that the details of this interaction must be determined by NASA and the program teams involved, and not imposed externally; the Study Group therefore refrained from specifying how this should be done. On the other hand, it is clear that much can be gained from the sharing not only of insights into success, but also insights into the lessons learned from past experiences, so that both human and material costs associated with frustration from wasted efforts (and even from failures) can be avoided.

D. Data Archiving and Distribution

Conclusion: Early planning of database architecture, tegether with institutional arrangements for data analysis and archiving, are essential elements of early mission planning, since they will affect the best way to carry out mission operations for the entire program.

Recommendation: The acquisition, analysis, distribution, and archiving of data should be a central part of mission planning from the beginning.

Discussion: Failure to plan for the ultimate scientific use of mission data diminishes the scientific productivity of the mission. The Study Group believed that rapidly advancing data-handling technologies offer great potential to return superior science at little or no additional cost, particularly for major observatory programs. Making effective use of the large data sets generated by a long-lived observatory requires explicit planning from the start of the mission. The involvement of both scientists and database experts will be necessary.

The key to making such data useful to the entire scientific community is the development of appropriate catalogs and directories that can be made available to the users at their home institutions. Organizations such as NSSDC can play an important role in this process, since their primary functions are ones of coordination, oversight, and facilitation of individual project initiatives. The development of catalogs, directories, and procedures for maintaining backup data sets will therefore be an important activity for NSSDC in the future. NSSDC can also perform a valuable service to project teams by providing advisory technical personnel with knowledge of the latest communications and data-processing technology, since this expertise is often lacking in groups devoted primarily to scientific research. NSSDC is actively involved with both the AXAF and SIRTF projects.

The Study Group also developed a number of specific recommendations designed to guide the development of data archives; these appear below under the heading, "Detailed Suggestions for Data Handling and Archiving."

OTHER CONSIDERATIONS AND CONCLUSIONS: RESPONSE TO THE STUDY CHARGE

Charge: (1) Analyze operations and data distribution for astrophysics missions as an integrated program across all major missions planned for launch before the turn of the century.

Discussion: During Phase I of the study, the operations of a number of missions were analyzed to identify common themes and elements; this analysis led to the graphic depiction of mission-operations functions described earlier in the present report. Such an approach permitted comparisons of apparently dissimilar missions and allowed the Study Group to bring past experience to bear on plans for AXAF and SIRTF. Of course, a more detailed and systematic study of future mission operations would be desirable. For example, the question of funding approaches for investigators requiring the use of more than one observatory for the acquisition of new data, for occasional simultaneous (or at least coordinated) observing runs, or even for studies requiring access to existing observatory data banks, remains a vexing and complex administrative problem. At present, NASA funds observers through each project; e.g., funding for use of HST will be allocated through STScI. NSF, by contract, funds groups to do research involving the use of ground-based observatories but leaves the allocation of observing time to the observatories' proposal-review process. It is clear that NASA must set up a mechanism to ensure that proposals involving more than one observatory are given proper consideration. Such a process should not be restricted to NASA projects, since coordination with NSF is also required. The Study Group tended to lean toward continuing with the hybrid system, provided NASA and NSF can develop a way for the responsible observatory heads to coordinate research and observing programs. If this is not possible, it may be necessary for NASA to consider changing its current, mission-oriented approach to one more like that of NSF. However, in the final analysis, agency-level coordination is essential. All approaches could benefit from more discussion than was possible during the course of the present study. The National Academy of Sciences has now begun a more extensive study, through a CSAA committee headed by Dr. Michael Jura of UCLA, that should address this topic in more detail.

Charge: (2) Examine the processing and distribution of data to enhance "problem-oriented" analysis of multispectral data from various missions at remote sites.

Discussion: Phase II of the study devoted considerable attention to the "problem-oriented" analysis of multispectral data. Two primary conclusions emerged. First, the standardization of data formats required for such analysis is already well advanced; largely through the efforts of NSF, the Flexible Image Transport System (FITS) format has become a world standard for astronomical data. Image-processing software is likely to be dominated by only two systems--the Astronomical Image Processing System (AIPS) system developed by the National Radio Astronomy Observatory (NRAO), already in wide use, and the Image Reduction and Analysis Facility (IRAF) system developed by the Kitt Peak National Observatory (KPNO), about to be released for use and expected to be widely adopted. Second, it was recognized that the recommendations of the 1982 CODMAC report are still entirely valid; the CODMAC report lists the steps NASA will need to take to facilitate the intercomparison of data from different missions. NASA is responding to many of the CODMAC recommendations, as discussed in the next section of the present report.

Charge: (3) Consider any beneficial role or use of existing or planned infrastructure, in particular the Space Station, the National Space Science Data Center (NSSDC), the Tracking and Data Relay Satellite System (TDRSS), and the Space Telescope Science Institute (STScI).

Discussion:

Space Station - The Study Group did not consider the future role of Space Station in maintenance and refurbishment, as the present study was limited to a consideration of data operations only. Since both AXAF and SIRTF are expected to be free-flying platforms, even though serviced by the Space Station and associated transportation systems, the direct role of Space Station in the operations of these missions is expected to be minor. There have been some preliminary proposals that the Space Station data system be "transparent," or configured so as to permit the operation of payloads as if they were in geosynchronous orbit. Such proposals embody features that are scientifically attractive to the astronomical community. However, the general structure of the Space Station data system is not yet sufficiently well defined to make clear whether such data plans are technically feasible for AXAF and SIRTF, or cost-effective for either project or for NASA. The Astrophysics Program should maintain a strong liaison with the Space Station Project to make sure that informed decisions are made.

NSSDC - The projected role of NSSDC is, as stated earlier, one of oversight, coordination and direct participation in selected cases. It is expected that NSSDC will support future Astrophysics mission operations by preparing data catalogs and directories, maintaining backup data sets, and providing advanced technical expertise to scientific study teams.

TDRSS - Both AXAF and SIRTF plan to use TDRSS for data transmission. At first glance, TDRSS appears to be capable of handling these tasks without significant interference from competing demands. The primary concern is the ability of TDRSS to maintain priority for Astrophysics operations in the face of other pressures for system use. Since the use of TDRSS for communications is scheduled only one week in advance, scheduling commitments for space observations may not in all cases be confirmed early enough to ensure that coordinated observations can be conducted. Since coordinated observations are extremely valuable, this issue demands attention by both NASA and NSF.

STScI - Discussion of the Study Group centered mainly on two areas. First, the group heard of the difficulties the HST team encountered during the first years of STScI operation; these accounts underscored the importance of an early choice of institutional setting and project-team involvement, as recommended earlier in this section. In addition, the Study Group was briefed on the extensive software that has been developed to support various aspects of HST operations. For example, STScI has taken the lead in adopting the standardized IRAF command language developed at KPNO, in the development of a data archival system employing new technology, and in the establishment of an astrophysics network. It appears likely that some portions of this software, or modifications of it, could be of direct use to AXAF and SIRTF.

DETAILED SUGGESTIONS FOR DATA HANDLING AND ARCHIVING

A study subgroup was formed to consider in more detail the steps that should be taken to facilitate the archiving and distribution of data. Their conclusions and recommendations are as follows:

1. Data acquisition, analysis, distribution, and archiving functions should be a central part of mission planning, spacecraft design, and design of the ground data system from the beginning. This effort should be funded and protected throughout the mission to allow continuity through completion.

2. The Astrophysics Division, NASA Headquarters, should support the establishment of a catalog and directory system in the near future. In particular, a study involving scientific users and others implementing the system should be conducted to establish requirements for astrophysics data catalogs and directories and to establish their feasibility. By the beginning of FY 1988, an on-line catalog and directory should be initiated that will accept data from all current and future missions.

3. Each project should be required to create, in addition to its local active research data base, a high-quality data product for deposit in an archive. This data product should be:

   - Prepared by people who work closely with the mission researchers and who have responsibility for updating the data.

   - Accessible to users who are not directly associated with the collection and processing of the data.

   - Well documented, providing for inclusion of both statistical errors and estimates of systematic errors.

4. A science steering committee should be established to oversee astronomical archival functions. It is anticipated that future astronomical data sets will be distributed among many physical locations but accessed through a centralized catalog and directory. The steering committee can play a particularly helpful role in ensuring that appropriate advanced technologies are employed in implementing such a scheme and in meeting user needs.

5. All data-access nodes should have the same degree of open access as does NSSDC after proprietary data rights have expired.

6. The procedures for selecting and funding investigators who require access to data from more than one observatory should be reviewed, and a workable system put in place.

7. The impact on science should be assessed before any major technological changes are implemented.

8. NASA should continue to make its resources readily available to the scientific community, including university researchers.

9. NASA should seek to exploit computing initiatives undertaken both inside and outside the agency, e.g., the establishment by NSF of a nationwide supercomputer network.

EXISTING INFORMATION BASE FOR STUDY

FINDINGS OF OTHER STUDIES

The National Academy of Sciences (NAS) and NASA have empaneled several groups in recent years to examine the processing of scientific data from spacecraft and to make recommendations for improvements. Seeking to build upon this past experience, the Study Group reviewed three NAS data and operations studies: Institutional Arrangements for the Space Telescope (The Hornig Report); Astronomy and Astrophysics for the 1980's (Report of the Astronomy Survey Committee, or the Field Report); and the report of the Space Science Board's Committee on Data Management and Computation (the CODMAC report). A bibliography of these and other related documents appears in Appendix C.

The Hornig Report

In anticipation of the development of HST, the Academy convened a committee, chaired by Donald F. Hornig, to examine institutional arrangements for the operation of this facility. The Hornig Report was issued in 1976 and therefore does not reflect experience acquired during the operations of IUE, HEAO-2, and IRAS. The Hornig Committee concluded that, while the operation of HST and its associated systems would best be carried out by NASA, optimum scientific productivity would require the close and continuous participation of the astronomical community. They urged specific institutional arrangements to provide long-term guidance and support for the scientific effort, a mechanism for engaging the participation of astronomers throughout the world, and a means for the dissemination and utilization of HST data. The Hornig Committee recommended that these needs be met through an independent institute, separate from NASA, operated by a consortium of participating universities. NASA accepted most of the recommendations of the Hornig Committee and proceeded to establish the Space Telescope Science Institute (STScI).

The Field Report

In 1978, the National Academy of Sciences convened, under the chairmanship of George B. Field, an Astronomy Survey Committee to develop priorities for a comprehensive program of astronomy and astrophysics for the 1980's. As part of their charge, the Astronomy Survey Committee also considered the future needs of the astronomical community for computational facilities. The Committee found that the increasing use of digital images in astronomy was creating a demand on computing capabilities that could not readily be met by facilities available at the time the Astronomy Survey was completed (1980). However, minicomputers and superminicomputers now on the market will be able to handle much of this load, if they are brought into operation at universities and research laboratories now. The Committee recommended that both universities and the Federal Government accelerate the timely acquisition and support of such computers. Many image-reduction tasks and theoretical calculations, on the other hand, require the capabilities of supercomputers. The Committee also recommended that Federal laboratories and observatories that have supercomputers continue to grant astronomers access to such facilities.

The CODMAC Report

The Committee on Data Management and Computation (CODMAC) advises NASA on ways to optimize the scientific return from its programs and missions through use of modern computing, archiving, and networking technologies. In 1982, CODMAC published the results of a study that identified several areas of concern within NASA, including planning, data processing, data distribution, standardization, and software transportability. Within data-system planning, CODMAC observed a lack of involvement by the scientific community, inadequate funding at the time of project conception, and an absence of overall planning. With respect to data processing, they found that most research groups were underfunded for data processing and analysis and thus could not acquire new technologies to exploit fully the information contained in their data. CODMAC noted that there were frequently long delays in the delivery of data to the user, and that delivered data were often poorly documented and calibrated. They also found a wide variety of data formats in use. Moreover, CODMAC discovered that costly software developments were often carried out to meet narrowly specific project needs, resulting in software that is not transportable to other users on the same project or to other projects.

As a result of the CODMAC recommendations, NASA Headquarters strengthened the Information Systems Office within the Office of Space Science and Applications (OSSA), consolidated OSSA information-management activities, initiated a number of pilot studies in several disciplines (including one in astrophysics led by STScI), and restructured the NSSDC. CODMAC also recommended that the user be actively involved from the inception to the completion of a mission; that scientific management incorporate some form of oversight by the scientific community; that data formats be governed by the needs of the user and reflect a balance between flexibility and economy; that ancillary data, such as pointing and engineering data, be readily available together with the scientific data; and that data be processed and distributed in a timely fashion. Emphasis should also be given to the acquisition and production of structured, transportable, and documented software. Scientific data should be stored in facilities that are adequately funded to ensure that the data are annotated and stored in a permanent and retrievable form. The resources for data analysis and processing should be set aside early in a project and should be protected from loss arising from overruns in other parts of a project.

EXPERIENCE FROM OTHER MISSIONS

Three missions--IUE, HEAO-2, and IRAS--have all been exceptionally successful from a scientific operations point of view, meeting essentially all of their expected operational milestones, and all have been operated in a different manner. The Study Group examined these missions in detail to identify any common factors that may have contributed to their scientific success. HST will be operated in a still different manner; although it has not yet been launched, the Study Group considered this project as well. A summary of program data for these four missions, as well as for GRO and SMM, is provided in Figure 2.

PROGRAM DATA/APPROXIMATE RESOURCES

	IUE	HEAO-2	HST	GRO	SMM	IRAS
STEADY STATE TOTAL OPERATIONS MANPOWER(MY)	98*	73	525	141	65	48* 83**
STEADY STATE OPERATIONS FY85$(M)	7	6	79	12	10	8
STEADY STATE INVESTIGATIONS	400	300	533	80	113	135
NUMBER OF INSTRUMENTS	2	5	5	4	7	2
DEVELOPMENT REAL YEAR $(M)	26.5	90	1185*	394	74	148****
DEVELOPMENT 85$(M)	55.3	189	1428*	417	129	237
CIVIL SERVICE DEVELOPMENT MANPOWER	919	568	2200	727	679	88
TOTAL DEVELOPMENT COST FY85$(M)***	147	246	1648	490	197	246
SPACECRAFT WEIGHT (LBS.)	864	6949	23741	34000	5105	2372
POWER (WATTS)	186	565	2525	2000	1500	250
DESIGN LIFE (YEARS)	3	1	2.5#	2	1	1
DATA COLLECTION RATE (KILOBITS/SEC)	20	6.4	1024	50	244	16.2

* U.S. ONLY
** EUROPEAN OPERATIONS MANPOWER
*** ASSUMES CIVIL SERVICE MANPOWER CONVERSION AT INDUSTRY RATE OF APPROXIMATELY $100K/MANYEAR
**** DEVELOPMENT COST TO U.S. WAS APPROXIMATELY $82M REAL-YEAR DOLLARS

\# ON-ORBIT SERVICING FOR EXTENDED LIFE

FIGURE 2

International Ultraviolet Explorer

The International Ultraviolet Explorer (IUE) was launched in 1978 to obtain high-resolution ultraviolet spectra of astronomical objects and continues to operate successfully 8 years later. Because of its location in near-geosynchronous orbit, IUE can be commanded in real time 24 hours per day. IUE, a cooperative program with the European Space Agency (ESA) and the Science and Engineering Research Council of the United Kingdom, is operated in two 8-hour shifts from the U.S. (GSFC) and one 8-hour shift from Europe (Vilspa, Spain). IUE did not have a Principal Investigator as such, but the leader of a team of scientists at GSFC worked with the Europeans and performed the functions of a PI. All of the observing time is available to guest observers, with no PI rights assigned to the instrument suppliers. The U.S. segment of the operation proceeds as follows:

a. Observing proposals are prepared and submitted to the IUE Project Office by potential users in the astronomical community in response to the annual "Dear Colleague" Letter. Proposal-instruction packages are sent to those interested.

b. When proposals for the forthcoming observing year are received, preparations are made for peer review, e.g., technical feasibility reviews, sorting by categories of research, and selection of peer-review panelists. The peer-review board recommends proposals for acceptance by the project and for final approval by the Astrophysics Division at NASA Headquarters.

c. The science program for the forthcoming guest-observing year is formed, and telescope scheduling is arranged for the proposals recommended by the review board.

d. When the guest observer comes to the IUE Science Operations Center (SOC) at Goddard, he/she fills out an observing script containing the information necessary for the operation of the telescope (e.g., the target's coordinates, choice of camera, and exposure time). Resident astronomers responsible for IUE planning are available for consultation at all stages of the process. Operating information is transmitted by the telescope operator to the IUE Operations Control Center, from which the commands are sent in real time to the IUE telescope. For relatively straightforward observing programs, the observer need not be present at the SOC but may choose to communicate with the SOC and receive quick-look data in real time.

e. Observational data are collected by IUE and telemetered to the ground, where quick-look data are displayed at the SOC observing console to aid the guest observer in enhancing his/her observational program. The overall operations of IUE are greatly simplified, and considerable costs saved, because of its location in geosynchronous orbit.

f. The telemetered data are processed on a computer at GSFC using calibrations that are updated periodically. The processed data products, in the form of magnetic tapes, Photorites and Calcomp plots, are sent to the guest observer for analysis and to NSSDC for archiving.

g. The data products are made available to any scientist in the astronomical community through NSSDC after elapse of a six-month proprietary period. The data are also available after six months to the users of Regional Data Analysis Facilities at GSFC and the University of Colorado. The analyzed data are made available to the astronomical community through publications.

High Energy Astronomy Observatory-2

HEAO-2, also called the Einstein Observatory, was an X-ray astronomy observatory consisting principally of an X-ray telescope with a 60-cm grazing-incidence mirror and four instruments in the focal plane. It was launched in 1978 into a low-Earth orbit and continued to operate until April 1981, when its control gas was expended. The mission began as a PI-type mission but was, before launch, expanded to include a Guest Investigator program. By the completion of data acquisition in 1981, approximately 25% of the observing time had been allocated to guest observers. The HEAO-2 scientific investigator team was made up of scientists from American Science & Engineering (AS&E), Columbia University, GSFC, and the Massachusetts Institute of Technology, united in a consortium under a single PI. Prior to launch, the PI and several members of the scientific team transferred from AS&E to the Smithsonian Astrophysical Observatory (SAO) in Cambridge, Massachusetts.

Because of the low photon flux, the HEAO-2 instruments operated in a photon-counting mode. This relieved the requirement for rigid instrument alignment and made possible an economical reconstruction of the X-ray images on the ground. The HEAO-2 data rate was 6.4 kilobits/second (kb/s). HEAO-2 had no real-time operations, so the expense of operating in real time in a low-Earth orbit was saved. The mission was operated from GSFC under the direction of the Marshall Space Flight Center (MSFC), the mission management center. That is, personnel from MSFC, TRW, Inc. (the mission contractor), and SAO, all resident at GSFC, conducted spacecraft operations. Scientific coordination and scheduling of operations was carried out at SAO. Mission operations plans were transmitted to GSFC, where the final command sequences and schedules were compiled. These were executed through a satellite control center at GSFC. The spacecraft required a minimum of two contacts per day for command loading and confirmation. The scientific data were decommutated, with timing added and attitude inserted, at GSFC. They were then transmitted to SAO for scientific processing and distribution to the scientific users (members of the HEAO-2 scientific team or guest observers).

Guest observers were selected competitively by NASA Headquarters and funded through MSFC. Both the Project Scientist and the SAO manager of the Guest Investigator Program participated in the proposal reviews. The observers selected generally spent some time at SAO becoming familiar with the HEAO data-processing system. Since no real-time operations were carried out, it was not necessary for the guest observer to be at SAO during the specific time of observation, but only a short interval thereafter, when the processed data arrived. The processed data were monitored by staff scientists at SAO to assure their quality. Because of the low-Earth orbit and the need to fix observing plans several weeks in advance, operational flexibility was rather limited on HEAO-2, a fact that led to simplicity and economy of spacecraft operations. The comparatively brief lifetime of the project required that the observing programs be laid out very carefully in order to minimize control-gas usage during target acquisition.

The detailed observing program was based on a target list produced at SAO, drawn from a unified observing catalog that included all the approved targets from the consortium institutions and from guest observers. Primary observing constraints involved keeping the solar arrays pointed within $\pm 30°$ of the solar direction and extending the satellite lifetime via momentum management. While satellite health and attitude were monitored at the GSFC Payload Operations Control Center (POCC) during real-time passes, real-time scientific operations and data analysis were not required, thereby simplifying requirements and reducing costs in these areas.

The Einstein data processing (which still continues) consists of two separate phases: pipeline processing with standardized software, and post-reduction scientific analysis performed by individual scientists. Pipeline processing involves data screening, application of calibrations, aspect solution, image creation and/or energy and temporal sorting of the data, and standard analysis to search for sources and fit simple energy spectra. Primary responsibility for generating the required software and for executing these activities resides at SAO, with scientists at GSFC and MIT responsible for handling the calibration and processing of their spectrometer data. Some instrument anomalies (e.g., drift of the aspect sensors in the Earth's magnetic field and gain variations in one of the focal-plane detectors) were discovered through analysis of flight data. To compensate for these, special calibrations were made on-orbit, data were analyzed, and software corrections were generated and applied retroactively to the entire data set. This ability to correct post facto for hardware and software anomalies is one of the major advantages of preserving the raw data and telemetering them directly to the ground for subsequent analysis.

The post-reduction scientific analysis is potentially a distributed function, although lack of portability of the Einstein software centralized much of this activity around the SAO computers for which the software was written. Improvements are still underway to better document the software and to provide for much greater portability and maintainability for future applications. All of the Einstein data are now part of a data bank, accessible by the entire scientific community. Substantial documentation is available in the form of user's manuals, cookbooks, and on-line help files; direct assistance in interpreting output and in selecting and applying off-line analysis programs is provided by SAO scientists and data aides. Users can also ask for specific scientific-analysis tasks to be performed for them remotely by SAO personnel, and the results are then mailed to them. Approximately 100 data-bank requests are generated and filled each year, and many substantial scientific projects continue to use the Einstein data archive.

Infrared Astronomy Satellite

IRAS carried a cryogenically cooled 0.6 meter telescope with 62 detectors in the focal plane to observe infrared radiation from astronomical sources. The spacecraft was launched on 25 January 1983 into a nearly circular orbit of 81.2 degrees inclination and 656 km apogee. It ceased operation on 24 November 1983 when its superfluid helium cryogen was depleted.

IRAS was a cooperative program involving NASA, The Netherlands, and the United Kingdom. The telescope, focal-plane assembly, and cryogenic system were provided by the U.S., The Netherlands provided the spacecraft, and the U.K. provided the control center and ground station via a bilateral agreement with The Netherlands. Focal-plane detectors were provided by the U.S. and The Netherlands. The spacecraft was launched by the U.S. on a Delta rocket.

The prime mission objective of IRAS was to survey the sky for infrared sources. In addition to the sky survey, more than 10,000 other observations were carried out. The IRAS scientific team was selected by NASA via an Announcement of Opportunity and combined with a team established by The Netherlands and the United Kingdom.

IRAS data were captured at the British ground station at Chilton, England and transmitted to the Jet Propulsion Laboratory (JPL) and the University of Gronigen for processing. The Infrared Processing and Analysis Center (IPAC), originally set up at JPL to process the U.S. IRAS data, was later relocated from JPL to the campus of the California Institute of Technology. The IPAC and its computational facilities are available for use by the IRAS investigators as well as by general observers selected by NASA to conduct research with the IRAS data. IRAS is an example of shared international responsibility for data processing and differs from the IUE example, in which the U.S. and ESA operate the spacecraft nearly autonomously during their shifts.

The all-sky survey had top priority for the six best orbits each day. The survey scans were generated automatically by software programs, and the periods of time that the telescope was not conducting survey scans were then filled with pointed observations defined by the Joint Science Team. All pointed observations were required to be repeated twice. The target areas and the observations were controlled by the Joint Science Team in order to eliminate duplication of targets and maximize science return from the telescope. Once defined, the scheduling of the observations was automatic via the mission-control software system.

Data processing was done in two locations. The real-time analysis and science quick-look were performed at the control center in England. The complete data stream from the satellite was expanded from 8 to 16 bits in England and then transmitted, via satellite links, to JPL in Pasadena, where the science processing and final product generation was performed. The survey data were processed into two primary forms. A catalog of point sources was generated which contains approximately 250,000 sources. The data were also converted into images by binning the sky flux and then generating images of the resultant data. These data were released to NSSDC in November 1984. One of the project requirements was to deliver to the community, within a year of the end of the mission, the final data products described above. These products were 'certified' by the Joint Science Team and delivered on schedule.

The IRAS data are continuing to be disseminated to the community via two primary paths. First, NASA has set up a General Investigator Program in which scientists selected by proposal review are funded to perform research utilizing the IRAS data. Project data-processing capabilities developed during the mission are made available for this program and are being converted from a production orientation to a scientific user orientation. Secondly, the U.S. portion of the Joint Science Team is continuing to play an active role by defining a second generation of products to be developed during the next four years (i.e., through FY 1989) using new processes that will increase the sensitivity of the catalog and the quality of the images. This advance has been made possible by actual study of the initial data, which supersedes the assumptions that were made before launch in developing the processing system used to deliver the primary mission products.

Hubble Space Telescope

The Hubble Space Telescope (HST) is being built as a general-purpose optical observatory in low-Earth orbit. The telescope is a 2.6 meter Cassegrain operating near the diffraction limit, with pointing and jitter requirements better than 0.1 and .01 arcsec, respectively. Its initial instrument complement consists of two cameras, two spectrographs, and a photometer, as well as star trackers that may be used for astrometry. The spacecraft is designed to be repairable in orbit, and the instruments can be removed by suited astronauts whenever more powerful replacements become available. Although some observing time is reserved for those scientists who participated in the development phase of the project, the principal use of HST will be as an international astronomical research facility that is available to any scientist able to submit a winning research proposal.

Although mission operations for HST can be described in terms of the generalized functions of Figure 1, some of these functions are considerably more complex or specialized in HST than has been the norm. A notable feature of the ground system is that the science operations have been split off from other parts of mission operations and made the responsibility of STScI, located in Baltimore and connected to the POCC at GSFC via high-speed ground lines. In general, those functions requiring either scientific judgement or direct interaction with the scientific community are assigned to STScI, while functions of spacecraft control, safety, and mission logistics are assigned to the POCC.

The STScI will annually solicit, process, and select research proposals from the astronomical community. Although the projections are very uncertain, it is anticipated that, in the beginning, 2000-3000 proposals may be received annually, necessitating acceptance rates perhaps as low as 10%. The successful proposals will be organized into a long-term observing plan for the year; this plan will then be broken into shorter intervals with increasing levels of detail, ultimately yielding a detailed weekly schedule with time-tagged slews, specific pointings, guide-star assignments, and associated instrumental command procedures. This schedule is transmitted to the POCC, where it is checked against various mission constraints, coordinated with the TDRSS schedule, and augmented by the spacecraft commands necessary to control the pointing, data-handling, and power subsystems. The integrated command load is sent to the spacecraft for execution at the appropriate time, and the resulting data stream is returned to the POCC. Scientific and calibration data are sent to STScI for routine processing and ultimate transmission to the scientific user. Engineering data are retained at the POCC for trend analyses that should be fed back into mission planning, but they are also sent to STScI for correlation with scientific data as needed. All HST data are archived at STScI, and extensive data-analysis facilities are available there for use by astronomers working with the data.

The HST ground system has a deserved reputation for being complex. However, it should be emphasized that the HST project has been characterized by unprecedented expectations in the areas of observer assistance and of data processing, analysis, and archiving. Never before has a NASA space-astronomy mission been expected to provide such an extensive array of user services beginning from the moment of launch. Some idea of the magnitude of the operation and data-handling tasks involved may be gained from a straightforward count of the computers installed at GSFC and STScI in order to implement the system as it will be configured at launch. These consist of three VAX 8600's, five VAX 785's, seven VAX 780's, one VAX 750, four PDP11-44's, and three IDM data-base machines. The duties of these various machines include tracking the status of research proposals, planning and scheduling the observing program, selection of guide stars, formatting command loads, receiving telemetry, real-time interactions and monitoring of spacecraft performance, and the calibration and preliminary analysis of data. Over two million lines of code are resident in these computers.

Some of the principal factors that have contributed to the complexity and cost of the ground system are summarized below.

a. High telescope performance and instrument complexity: This has been a major driver in operations costs, since the in-orbit hardware places high demands on the ground system. The pointing requirements have necessitiated development of a hard-line accessible, all-sky catalog containing some 20 million stars with positional accuracies of 0.3 arcsec and photometry to 0.25 magnitude. No catalog of this scope and accuracy has ever been attempted before, and a substantial research effort was needed just to develop the techniques necessary for its compilation. Each of the five scientific instruments is highly sophisticated, with many operational modes requiring unique commanding procedures and calibration algorithms. The ground software needed to manage these instruments and data are unavoidably complex.

b. Interactive and preplanned observing: The choice of both preplanned and interactive observing modes on HST has required two operational systems to be developed. This, of course, has significantly increased the scope of the ground system.

c. Observing efficiency: Typical exposure times will range from 5 to 30 minutes, in contrast with other major observatories, where pointing durations have been measured in hours or even days. The HST ground system must consequently be prepared to schedule and manage a continuing high level of spacecraft activity. The tools necessary to do this must themselves be comprehensive and efficient in order to make effective use of HST observing time.

d. Inexperienced users: Most of the scientists using HST will not be experienced in the complexities of scheduling and operating a spacecraft in low-Earth orbit. The users will therefore need extensive, expert support in defining and executing their observations and in interpreting their data. This situation requires a much larger staff than that of previous PI-class missions, where operations and data analysis have been performed by a small team of experienced instrumentalists.

e. Lack of input from operations group during early design: The original ground-system design did not include a number of capabilities later deemed essential by the mission and science operations teams. Post-facto upgrades to the hardware and software systems have been expensive to implement, and frequently controversial.

f. Inability to compromise: Because of the lack of a single scientist with the project-wide knowledge and authority to make cost/benefit tradeoffs in the area of scientific performance, the ground system was developed in response to diverse and sometimes conflicting scientific pressures, with attendant escalation of complexity. It would be desirable to develop a more effective process for defining scientific goals and assigning priorities.

g. Software Generation: There has been much discussion critical of the cost of contracted software development, particularly from members of the scientific community with experience in computer programming for their own scientific research. However, the HST ground software sytem is large, complex, and must be maintained and operated for many years by persons other than the developers. It is essential that such a system go through rigorous definition, design, and interface control and that it be extensively documented. This is inherently an expensive process that is usually avoided in smaller systems developed by individuals or small teams for their own use. However, these development costs are amply justified in a major operations system that must be trouble-free and maintainable for the life of the project.

Many of these factors affecting ground-system complexity are unique to the HST project and need not be of concern to other future missions. It should be remembered, however, that actual flight experience will undoubtedly reveal advantages and deficiencies in the ground system that are not anticipated before launch. It will certainly be worthwhile to examine operations plans for future missions in order to apply lessons learned from HST operations where they are appropriate.

SUMMARY DESCRIPTIONS

Advanced X-Ray Astrophysics Facility (AXAF)

AXAF will be a free-flying, long-lived X-ray space observatory operated as a national observatory for use by the astronomy community. AXAF will consist of a telescope made up of six nested, grazing-incidence, Wolter Type-I mirror pairs, tegether with a focal-plane assembly capable of holding four large X-ray instruments. Only one instrument will operate at a time. This will be accomplished either by rotating the focal-plane assembly or by moving the X-ray mirror assembly to focus X-rays onto the appropriate instrument. The outer mirror will have a diameter of 1.2 meters and a focal length of 10 meters. The mirrors will have an on-axis effective area of 1500 cm^2 at 0.5 keV and 200 cm^2 at 7 keV to yield an angular resolution of 0.5 arcsec; however, since AXAF operates in a photon-counting mode, the spacecraft requires a pointing accuracy of only 30 arcsec. The images are reconstructed post facto on the ground to a precision of 0.5 arcsec.

Five instruments have been selected for definition on AXAF:

a. Microchannel Plate High Resolution Camera;

b. Charged-Coupled-Device Imaging Spectrometer;

c. High-Resolution X-ray Spectrometer;

d. X-ray Calorimeter Spectrometer; and

e. Transmission-Grating Spectrometer.

The AXAF scientific payload will have an average data output of about 32 kb/s, transmitted through TDRSS. Spacecraft operations, initial data capture, and processing will be conducted by MSFC/AXAF Project via the multimission POCC facilities at GSFC. Science operations will be conducted via a distributed SOC under the management of MSFC. Telescope scheduling and command sequencing will be compiled and loaded into the spacecraft on a predetermined schedule. No real-time observations will be carried out by AXAF, and quick-look data will be required for housekeeping purposes only.

AXAF will be launched by the Space Shuttle into an orbit of 28.5 degrees inclination and an altitude of approximately 600 km. It has a lifetime of 10 to 15 years and will be serviced and have consumables replenished through Space Station servicing. The AXAF Project is managed by the NASA Marshall Space Flight Center.

Space Infrared Telescope Facility (SIRTF)

SIRTF is planned as a long-lived, free-flying space observatory for infrared astronomy, to be placed into orbit in the early-to-mid 1990's. It will operate as a national facility, with the bulk of the observing time allocated to general investigators. The SIRTF telescope and instruments will cover the infrared spectral region from 1.8 to 700 microns. The optics and focal plane will be cooled by superfluid helium to below 5 degrees Kelvin. The primary mirror will have a diameter of approximately 0.85 meter. The telescope will be diffraction-limited at wavelengths longward of 2.5 microns. It will have a field of view of 7 arc-minutes and a pointing accuracy and stability of 0.15 arcsec. SIRTF will be capable of tracking Solar System targets at rates up to 0.21 arcsec per second.

The cryogenic cooling of the SIRTF telescope and the freedom from atmospheric emission and absorption will permit observations over the 2-200 micron band to be limited in sensitivity only by the faint natural infrared background in the Earth's vicinity. This low background environment, the long integration times provided by SIRTF, and the state-of-the-art detectors will make SIRTF 1000 to 10,000 times more sensitive than the Infrared Astronomical Satellite (IRAS).

Three instruments are under definition study for SIRTF:

a. An infrared array camera that will provide wide-field and diffraction-limited imaging over the 2-30 micron spectral band.

b. An infrared spectrometer that will provide moderate resolving power (100-500) from 2.5 to 200 microns, and higher resolving power (more than 1000) from 4 to 120 microns.

c. A multiband imaging photometer that will provide photometry and imaging of very high sensitivity and spatial resolution from 3 to 200 microns, and lower-resolution capability from 200 to 700 microns.

Observing time will be block-allocated to instruments according to preprogrammed scheduling and observing sequences, thereby eliminating real-time interaction with the instruments and simplifying operations. Only one instrument will operate at a time. Unallocated observing time and slewing time will be used for surveys.

SIRTF will be launched by the Space Shuttle and an Orbiting Maneuvering Vehicle into an orbit of 28.5 degree inclination and 900 km altitude. The lifetime with the initial cryogen load will be in excess of 2 years; on-orbit cryogen replenishment will be used to extend the lifetime, with a 5-year requirement and a 10-year goal. Instrument changeout on orbit is not envisioned. Cryogens will be replenished and other servicing carried out by the Space Station.

Data from SIRTF will be returned via TDRSS at an orbit-averaged rate of approximately 50 kb/s, with a peak rate of 300 kb/s. GSFC will provide level-zero data processing and mission operations and control using multimission support facilities. Scientific operations and detailed data processing and distribution are to be carried out at the NASA Ames Research Center (ARC), which manages the SIRTF Project.

EXPERIENCE OF OTHER COMMUNITIES AND ORGANIZATIONS

The community of planetary scientists and operations personnel has recently conducted a study of mission operations at JPL which is of some relevance to astrophysics missions. Comparisons with the JPL findings show, for example, that manpower requirements for the operation of HST are approximately equivalent to those associated with a major planetary encounter (peak level of 500 man-years/year). In addition, NSF has gained experience in the processing, archiving, and distribution of data to the astronomical community through their support of ground-based astronomical observations.

The Planetary Community

The planetary community is currently examining ways to reduce the cost of mission operations and data analysis, and to assure the preservation and easy accessibility of data from past planetary missions.

The rising cost of planetary missions has made it increasingly difficult to receive "New Start" approval for future projects. In response, the Solar System Exploration Committee of the NASA Advisory Council has recommended a series of comparatively modest planetary missions based on the commonality of two spacecraft: The Planetary Observer and the Mariner Mark II (MM II). The Planetary Observer is approximately equivalent to a Pioneer-class spacecraft, whereas the MM II is Voyager-class in scope. The Observers would have data rates of 10 to 20 kb/s, while the MM II data rates would be about 50 to 100 kb/s. Within an annual funding envelope of $300M in FY 1984 dollars, one Observer could be started every two years and one MM II started approximately every three years. The problem facing the planetary community and NASA is to constrain the MO&DA costs to a level of about $60M per year without compromising the scientific return from the missions.

The NASA Solar System Exploration Division and JPL initiated tradeoff studies to examine some of the cost factors associated with the mission operations and data analysis. The major cost factors they identified and examined were: organization, increased multimission functions, automation, sharing among similar projects, spacecraft commonality, data-system standards, and early operations involvement in projects. The NASA/JPL team concluded that a single-project organization for the Observer spacecraft and a single project organization for MM II offered the best organizational structure. A single-project organization for each type of spacecraft brings the continuity and experience of prior missions to new missions, provides the motivation to do a good job on a series of missions, and furnishes an incentive to maximize spacecraft commonality. With regard to data systems and data handling, the team examined and recommended adoption of seven data-system standards: telemetry-channel coding, packet-telemetry formats, packet telecommanding, time-code formats, radio and frequency standards, radiometric and orbit data formats, and standard-format data units. These standards will promote more automation and sharing among projects, simplify software changes from mission to mission, and simplify data archiving.

A problem that appears to be common to many missions is the absence of early involvement of data-handling specialists in the project. The scope of mission operations is set early in the project life by the science goals, mission profile, and spacecraft design. Early projections of operations costs are often unrealistic because the projects tend not to fund data operations adequately early in the mission, when critical data-system planning and design should take place. There is frequently no realistic model of operations costs specifically constructed to be a function of science, mission, and spacecraft parameters. The NASA/JPL group concluded that the implementation of their recommendations could reduce the MO&DA costs for the core planetary program recommended by the Solar System Exploration Committee to less than $60M per year.

A second concern is the preservation and accessibility of data from past as well as future planetary missions. The planetary community fears that, because of poor documentation, deterioration of the data medium, lack of an organized archival system, and personnel changes, important data are already being lost. In addition, the use of data has been limited by difficulties in identifying and locating particular data sets, finding supporting documentation, and computational problems in manipulating the data. In December 1983, the NASA Solar System Exploration Division organized a community-wide workshop to address these questions. The outcome of the workshop was a recommendation to NASA to develop a Planetary Data System (PDS). A committee was convened and a plan for PDS developed. The PDS, as planned, will be a hierarchical structure of nodes, consisting of a central management structure to assure conformity to standards. The central node will be responsible for the storage and distribution of planetary data sets and for providing a dial-in directory and catalog. A mission center will maintain the interface between the PDS and a flight project and discipline center in order to provide oversight of data sets relating to a particular scientific discipline. Special study nodes can be set up to attack specific scientific problems. In no case is it intended that the nodes or centers will be permanent facilities, but rather that centers will come and go as the need arises. The PDS was recently combined with the Planetary Data Pilot Study and is in the process of implementation.

National Science Foundation

NSF is the lead Federal agency for support of ground-based astronomy. The national astronomical centers supported by NSF are the National Optical Astronomy Observatories (NOAO), the National Radio Astronomy Observatory (NRAO), and the National Astronomy and Ionosphere Center (NAIC).

These observatories generally make allocation of observing time to scientific programs described in peer-reviewed proposals. If a proposal is accepted, the proposer is given telescope time to accomplish his/her observations. Within the general constraints of the scientific objectives of his/her proposal, the observer is given discretion in the allocation of the telescope time among various targets. This practice stands in contrast to the allocation of time for observations of a specific source, as is the usual space-observatory case. This same level of discretion extends to the reduction of the data, which in most cases effectively remains under the control of the observer who recorded it.

Traditionally, photographic plates are considered to belong to the observatory where they were taken, and are loaned to the astronomer who took them. Once the data of interest have been analyzed, the astronomer is expected to return the plates to the observatory. Because of their great value, photographic plates, when returned, are archived under carefully controlled conditions. Computerized lists of photographic plates, both those still on loan and those in the observatory archives, are maintained.

On the other hand, data recorded either in analog or digital form--but not on photographic plates--have traditionally belonged to the observer who obtained them. No effort is made to archive these data, other than noting in the observing log of the telescope that such data were obtained.

Since the early 1980's, more and more observations have been made with nonphotographic detectors, such as scanners, Reticons, and charge-coupled devices. Following the established tradition, these data are considered to belong to the observer, and no effort is made to archive them. NOAO initiated development of an Image Reduction and Analysis Facility (IRAF) for extraction of information from digital images. IRAF is undergoing continuing development at NOAO and has been adopted by STScI. It will be made available to the astronomical community in a transportable, standardized version.

The situation at the NRAO is quite different. Radio-astronomy data are exclusively in digital form, and radio astronomers rely heavily upon computer-based image processing and analysis. The Very Large Array (VLA) may produce more than 100 gigabytes per year of raw data, which are stored in the VLA archives. These data are compressed into images and given to the observer for reduction either at the telescope site or at the observer's home institution. NRAO has develped the Astronomical Image Processing System (AIPS) as an image-processing executive to aid the analysis of digital images and has produced transportable versions which have been distributed to over 100 institutions around the world. In spite of the data-compression techniques employed by NRAO and the availability of supercomputers, the data-production requirements of NRAO exceed the in-house computing capability. Steps are being taken to increase astronomers' access to supercomputers, but, at present, some data are not analyzed as thoroughly as they might be.

NSF-funded centers also played a key role in the development of the Flexible Image Transport System (FITS), a standardized format for exchanging digital images which is universally recognized around the world and has been adopted by the International Astronomical Union.

INFRASTRUCTURE RELEVANT TO THE STUDY

Considerable support infrastructure relevant to astrophysics mission operations and data handling is either already in place or will be in place by the time AXAF and SIRTF begin to return scientific data. Here we discuss the roles of NSSDC, STScI, TDRSS, and Space Station.

National Space Science Data Center

Following its reception at a ground station, the spacecraft data are first processed at a NASA facility to remove data overlaps, to identify dropouts, and to convert the data into a form that can be further processed by the user. This function is carried out by the NASA Office of Space Tracking and Data Systems. Extensive computational facilities have been developed at GSFC and JPL to carry out this function for space-science missions. In a typical PI mission, the data are processed by GSFC or JPL and sent directly to the PI, who then proceeds with individual scientific analysis.

With the advent of guest-observer programs, such as those associated with IUE, HEAO-2, and IRAS, the typical service of the GSFC and JPL information-processing divisions was extended to encompass project-specific facilities: at the Smithsonian Astrophysical Observatory in the case of HEAO-2, at the California Institute of Technology in the case of IRAS, and, in the case of IUE, within the GSFC Space and Earth Sciences Directorate. Mission planning is carried out by the project management office directly at the operations control center in the case of many PI-class missions, or in one of the extended science operations centers, as is the case with HEAO-2, IUE, and IRAS. Similarly, dissemination to the user is carried out by the NASA data-processing facility directly, or by one of the extended centers for IUE, IRAS, and HEAO-2. After a specified period of time (typically 6-12 months), the data become accessible to other users. This is typically done through NSSDC, although in the cases of IRAS and HEAO-2, the data archives are maintained by the mission-unique centers. Guest observers may either come to the center, or request specific blocks of data from the center and have them mailed to their home institutions. At the conclusion of his/her time of proprietary use of the data, the PI is required to deposit the data in NSSDC in a form usable by other interested scientists. This requirement has not always been fulfilled, both because the PI would rather spend limited funding on the prime analysis itself or because NSSDC had neither the staff nor the facilities to receive, catalog, and archive all the data from Space Sciences and Applications missions. CODMAC recognized the existing limitations of NSSDC and recommended that NASA restructure it to more closely correspond to more reasonable functions.

In consonance with this recommendation, GSFC undertook, in 1984, a major restructuring of NSSDC. A new organization and facilities are in place, and plans are being generated to improve NSSDC participation in the total process of data generation and handling. NSSDC will endeavor to be an active participant in all missions from their inception, providing staff members to project data panels and participating in the early development of plans for project data management and archiving. NSSDC will also, in certain cases, be actively involved in the development of data systems.

NSSDC intends to pursue agressively database management techniques for handling space-science data and to introduce state-of-the-art mass-storage technology for active archive capability. NSSDC will increase outside scientific community participation by encouraging active space scientists to join NSSDC as detailees or as Resident Research Associates, and they will provide research facilities for visiting scientists.

Space Telescope Science Institute

STScI represents an organization unique among those involved in the operation of Astrophysics spacecraft. STScI, located on the campus of Johns Hopkins University in Baltimore, is operated by the Association of Universities for Research in Astronomy (AURA) under contract to NASA. It is headed by a Director appointed by AURA and is overseen by an AURA visiting committee. The Institute has a staff of scientists and data-processing personnel, together with computing facilities to carry out operating responsibilities. The AURA contract for STScI is the responsibility of the HST Project at GSFC.

Among its many responsibilities, the STScI will manage the HST data distribution to general observers, operate the HST data archive, and support archival research. The STScI will solicit and select proposals for the use of HST and distribute funds for the support of U.S. observers. General-observer proposals will be peer-reviewed by the STScI Telescope Allocation Committee, and selection will be made by the Director. The STScI staff will plan and schedule the HST science program as defined by peer-review selection and will, themselves, conduct scientific research subject to the same criteria. STScI is developing the science data analysis software (SDAS), the Guide Star Selection System (GSSS), the calibration database software, the proposal control processor, and the optical-disk storage system. They also have responsibility for the maintenance of the science operations ground system (SOGS), and they are cooperating with GSFC in the development of the data archive and distribution system (DADS). STScI has the staff and facilities to perform major data-processing tasks and to provide user-support services required for a major astronomical mission.

Tracking and Data Relay Satellite System

The Tracking and Data Relay Satellite System (TDRSS) provides the prime data link to the ground from spacecraft operating below geostationary orbit. Consequently, HST, AXAF, SIRTF, and other planned Astrophysics missions will use TDRSS as a transmission link for commands and data return. When fully operational, TDRSS will consist of two spacecraft in geostationary orbit, located at 41 degrees west longitude and 171 degrees west longitude. This placement yields coverage of the entire globe except for a "zone of exclusion" of approximately 20 degrees centered at 75 degrees east longitude. The TDRSS ground terminal is located in White Sands, New Mexico. Data will be transmitted from the scientific spacecraft to TDRSS to the ground station, and from the ground station to GSFC or to some other user location for reduction. TDRSS provides two classes of service, multiple access and single access, and can support up to 20 multiple-access channels simultaneously, each at a maximum data rate of 50 kb/s for data return. Commanding and forward link communications is done through a single channel operating at 10 kb/s. Multiple access will operate at S-band. Single access--dedicated access for a single user--is capable of providing 300 Mb/s data return and up to 25 Mb/s for commanding and communications to the spacecraft. Single access will be used on a shared priority basis and normally will not be available for dedicated support of any mission. Single-access service operates on both S-band and Ku-band. TDRSS is also capable of providing standard tracking services for orbit determination. Approval for the use of TDRSS and scheduling of services will be handled by the NASA Office of Space Tracking and Data Systems in a way similar to that now used for approving and scheduling the services of the present Spaceflight Tracking and Data Network. A major problem associated with the use of TDRSS is that times of communication are scheduled only one week in advance, so that times for coordinated observations by HST, other satellites, and ground-based observatories will be constrained. If these valuable observations are to be pursued, NASA and NSF must work toward developing a more flexible approach for TDRSS/observatory operations.

Space Station

The charge to the Study Group requested the Space Station be examined for its relevance to the data operations of future Astrophysics missions. However, the Space Station data and communications systems are still evolving, and their usefulness to specific Astrophysics missions cannot yet be assessed. The report of an Astrophysical Data Requirements for Experiments on Space Station (ADRESS) working group was made available to the Study Group. In general, the Study Group endorses the ADRESS recommendations that the Space Station data system be as transparent as possible to the user and that a scientist be able to operate an experiment on the Space Station as if it were in the laboratory next door. However, careful cost tradeoffs and informed decisions must still be made.

PHASE III: COMMUNITY RESPONSE

Phase III of the study consisted of a solicitation of views on the Phase II conclusions and recommendations. Over 270 individuals representing the broader Scientific community and NASA management were sent copies of the preliminary (30 January 1986) draft report for their comments and suggestions. Twenty-nine responses were received, ranging from brief, one-paragraph commendations through detailed, six-page critiques and commentaries. Numerous suggestions for clarification or for editorial changes have already been incorporated into the present, final text. Other issues raised by the draft-report reviewers are discussed in this section under the following headings:

- Two especially thoughtful replies;
- Overview of other responses;
- Participation of the planetary community;
- Sharing of experiences by mission teams;
- Missions other than those examined;
- Basic management principles;
- Data issues and computation;
- Hubble Space Telescope and STScI; and
- AXAF and SIRTF.

A summary of the Phase III findings completes the section.

TWO ESPECIALLY THOUGHTFUL REPLIES

Two letters stood out as particularly thoughtful, relevent, and constructive. They are worth quoting at length. From a solar physicist:

"The report is well written and has several excellent recommendations. Of particular importance are the first two concerning early involvement of the science and operations team, and adequate staffing and management simplicity with clear lines of authority. The reason for flagging these is that these two factors were a key to the success of the solar part of the Skylab mission flown in 1973-74.

"I suspect that scientific operation of the Skylab solar telescopes (ATM) was far more complex than any of the examples given in the report. There were six primary scientific instruments, each with multiple operating modes (one with over 100 options) that typically were changed every few minutes. In addition, there were two pointing telescopes, one with a film camera. During manned intervals (about 12 hr per day) most, sometimes all, of these telescopes were operated simultaneously. Several of them were also run by commands from the ground during unmanned intervals yielding 24 hours per day (during daylight part of orbit) for 9 months. Adding to the operational complexity was the fact that conditions on the target (Sun) varied with time. Thus, observing programs had to be developed each day by the scientific team and then often modified in real time in response to solar events such as flares. The HST operation will be complex--will it be more complicated than Skylab?

"The Skylab experience is relevant because mission operations for the solar experiments were highly successful. The reason they were successful was that from the very beginning of the program a small core group of scientists concerned with scientific operation of ATM was involved in determining how the mission would be run. These scientists worked with a NASA operations team that had highly motivated and competent individuals with clear lines of responsibility and authority. The combined PI science teams (involving five institutions) and NASA team worked together very smoothly--not only because of the dedication of the individuals involved, but also because of the clearly defined responsibilities and lines of authority. For example, to interface effectively with the NASA team during the mission we utilized an ATM 'czar,' one individual who the NASA flight team turned to for scientific and operational decisions on what to do with ATM. This person was for ATM science what the flight director was for Skylab as a whole, the person where the buck stopped. In effect, the ATM czar was the equivalent of a PI on a single experiment, only in this case the experiment was an entire observatory, ATM. (In order to operate 24 hours per day over many months, the ATM team rotated the czar position among several individuals selected by the individual instrument PI's from the pool of scientists in the five instrument groups.)

"A second reason for the success of ATM was the use of a problem-oriented approach to design of scientific observing programs, the Joint Observing Programs. This was, I believe, the first major multispectral problem-oriented undertaking in space astrophysics. (The only other mission flown thus far that approaches ATM in scientific operational complexity most likely is SMM.) Several years before flight, we found that the only way to proceed with ATM was to use a problem-oriented approach. It greatly simplified decision-making in developing observing programs, determining what features to observe on a given day, and how to configure the instruments for making observations in a given block of time."

Another letter, from an X-Ray astronomer, commented as follows:

"I did want to stress an issue which the report recognizes, but which I feel should be stressed even further. That is the degree to which data reduction and analysis are intimately connected with the scientific activities of the post-launch phase. In a laboratory, an experimental scientist can continually improve his/her instrument, taking advantage of what he/she learns from one measurement to enhance the yield of the next one. Space scientists have not had that luxury, although the advent of replaceable instruments does give some opportunity for upgrading, but on a five year timescale. So nearly all the optimizing and improving must be done on the ground -- in the reduction and analysis software. As one understands better the on-orbit operation of the instrument and the phenomena under observation (often newly discovered and therefore unexpected), one can improve the software to enhance the scientific yield. Every astrophysics mission I am aware of has benefitted from this kind of activity, and without it some discoveries would not have been made.

"I am convinced that this kind of activity is best carried out when the scientists are directly involved in, and even to some degree in control of, the DRA process. There is a direct analogy to the phase of instrument design and development. NASA recognizes that the best results are obtained when a PI is given sufficient control so that he/she can exercise scientific judgement in the miriad of cost, schedule and performance tradeoffs that occur during the preparation of an instrument. I submit that this is no less true in the post-launch phase. Of course, in both cases there must be sufficient project control by NASA to insure the quality and timeliness of the project. But this should not extend to detailed technical control.

"The AXAF project has been formulating plans for a distributed 'SOC' that would embody the principles I have outlined. I think the report should encourage and support these principles as well."

OVERVIEW OF OTHER RESPONSES

Of the remaining 27 responses, eighteen (two from study-team members) generally praised the study and its recommendations; nine (three from study-team members) were neutral, non-committal, or offered editorial suggestions only; and two were skeptical or critical. Here is a sampling:

- "In general, I found that it correctly pinpoints many of the issues that are relevant to future missions in the era of the Great Observatories. . ."

- "I find myself in general agreement with the conclusions and recommendations. . . On the whole, a very good job. . ."

- "I have read the draft report on Astrophysics Data Operations, and I wish to commend you and the members of the Study Group on the excellent work which you have done in generating this report. I strongly concur with the general conclusions and major recommendations and look forward to working with NASA to implement them on AXAF. . ."

- ". . .I am happy to see that the general issues of integrating long-term observations into early mission planning are being studied. It indicates that NASA is realizing that there's more to our efforts than just 'getting the bird off the pad'. . ."

- "Generally it is an excellent report that should be widely read. Hopefully it will dispel all fears of high operational costs for future astrophysics missions. . ."

- "It is pretty impressive--in general, your group seems to have gotten a lot of the basic problems down on paper. It would be great if these ideas insert themselves into the future flight projects! . . ."

- "My general opinion, after reading the Draft Report, is that the group did an excellent job in gathering and assessing information from a very wide spectrum of sources, and they synthesized same into a clear, thoughtful, and objective report: quite an accomplishment!. . ."

- "The subject report on Astrophysics Data Operations looks to us like a good product. JPL's experiences in working with the Astrophysics, Oceans, and Planetary communities during IRAS and SEASAT, and in the formation of IPAC and the Oceans and Planetary pilot data systems corroborate the principal findings in the report. . ."

- "I have read it from cover to cover and believe it is an excellent report. Over the years I have seen other excellent reports. Some of these have affected policy but others have never been implemented. I hope you will be able to follow the guidelines set down in this report. . ."

Two responses stood in sharp contrast to the generally favorable drift of the others. Neither writer had been involved in any of the study discussions, but both stated views that have been expressed over the years by some NASA managers and by a number of non-NASA scientists. These comments are provided here for completeness and to illustrate that opinions contrary to those expressed in this report continue to be held:

- ". . .the assertion that it is the scientists who are in the position of ensuring that 'optimum cost tradeoffs' are made is patently absurd. The users would like the last one percent of performance out of systems--the one percent that amounts to fifty percent of the cost."

Later in the same letter:

"I have read many reports like this one since coming to NASA, and they all have one common characteristic: advocacy of the principle that most decisions should be driven by those people who have the least responsibility for them. NASA recruits, trains, hires and assigns the best people they can find to manage programs, projects, and experiments--people who are then told implicitly but repeatedly in reports like this one that they are the least qualified to make the right tradeoffs and decisions. I wonder how much attention would be paid by anyone to a report compiled, authored, and edited by NASA managers and engineers on how well the community of scientists perform their roles in the implementation of flight programs?. . ."

From another letter:

- "Most, perhaps all, of the conclusions and recommendations of the report seem unexceptionable. The strong emphasis of the importance of early choices of the institutional settings for AXAF and SIRTF is especially wise. But early wrong choices could cost a lot in performance and real expense. . ."

Later in the same letter:

> "NASA centers are structurally incapable of efficient development and maintenance of scientific software systems of the complexity required for AXAF and SIRTF. I therefore think that the Hornig recommendation 5, that the institutional arrangements be managed independently of and under contract to NASA, should be strictly followed for AXAF and SIRTF, even though the scale of the institutional arrangements needed for these future missions is certainly much smaller than that required for HST. . . I detect in the report. . . an effort to weaken the central thrust of the Hornig recommendations. I hope that is not your intention. . ."

PARTICIPATION OF THE PLANETARY COMMUNITY

The study had explicitly included discussion of JPL's experience in examining the management and costs of planetary missions. However, two reviewers felt this was not enough:

- ". . .the management of Code EZ (Astrophysics Division) has made a major error in not involving the 'real' astronomical community in this work--the 'real' astronomical community includes a substantial fraction of planetary astronomers, and the special knowledge and experience of these people has apparently been ignored. . . For example, there is not a. . . practicing Solar System astronomer in the study group. . . . Thus the experience generated by these people in successful programs on OAO's, IUE, IRAS and HST planning has not been considered. How this happens, when it is well known that many of the most interesting and exciting discoveries made by some of these missions are in the Solar System field of interest--I frankly don't understand. . ."

- "It was surprising to see no reference to planetary mission management experience. Their projects have always been very large, and it would seem appropriate to review their experience before proceeding with another very large Astrophysics mission. . ."

SHARING OF EXPERIENCES BY MISSION TEAMS

One reviewer wrote as follows:

- "Each mission's planners assume they must re-invent the wheel, so your conclusion that management experience can be shared is a very important one, and it should be incorporated into NASA's procedures somehow. Now if we can only believe someone from a discipline other than our own!. . ."

Another reviewer wished to qualify the report's observation that different mission groups are often unaware of one another's experience:

- "I would agree in general, but note that this does not hold for the planetary missions. In my experience on two planetary review boards . . . I find a remarkable awareness of lessons learned in the past from previous JPL projects. There is an almost amazing familiarity of 'new project' people with the past problems of 'old project' people . . . And so, I would suggest the notion and value of '<u>program continuity</u>' to the role of NASA field centers. . ."

MISSIONS OTHER THAN THOSE EXAMINED

A number of reviewers commented on missions not specifically targeted for discussion in the report:

- "Though I suppose the Committee was specifically directed to concentrate upon AXAF and SIRTF, I wondered why no attention is paid here to the planned operation of GRO. After all, GRO comes before SIRTF and AXAF. It is felt that GRO is such a distinct class of experiment that our past experience does not relate to it in the same fashion that it does to these two missions? Or have all the plans already been made? Perhaps it's entirely a separate issue. . . But its absence from a document such as this is curious. . ."

- "Did the committee consider how SMM was managed? Remember, from the start, the assignment to Goddard [Space Flight Center] of 70 scientists from eight institutions was touted as a great thing for analysis of multispectral data. From my own experience there, I can say that that aspect of the program went well. . ."

- "As I read the report I was impressed again by one central point, the commonality of the data management concerns of the various science disciplines which use space-derived data. Many of the concerns of the astronomers are identical to those in the two disciplines with which I'm most familiar, solar-terrestrial physics and planetary physics. In implementing a data plan for future astronomy missions, I think it is important to build on recent experiences in the other space-science disciplines, not just previous astronomy missions. In particular, I think that recent work by the NASA data pilots may be very applicable, especially the work on imaging data from the Planetary Data System. . ."

BASIC MANAGEMENT PRINCIPLES

All reviewers who addressed this topic agreed with the report's recommendation for management simplicity:

- "I concur with the emphasis on simplicity of management scheme. . . I feel that considerable effort and money was wasted by the decision to split HST between Goddard and Marshall. If this must be done again in AXAF or SIRTF, at least appoint a single person with absolute authority to override all other elements of the project, wherever located. . ."

- ". . . I am not in a position to comment on much of the analysis in the report or many of the detailed recommendations. However, I am impressed by the care and thoughtfulness with which the problem has been addressed. I concur most strongly with the emphasis on management simplicity and the early establishment of well defined decision making structures. I also concur with the recommendation for early involvement of operational and scientific personnel in the definition, development, and implementation of each mission. . ."

- "To improve the report, you might consider how the conclusions can be sharpened. Regarding the 'application of basic management principles,' could you spell out the ones the committee had in mind? How do you view streamlined PI structures vs. committee management, which sometimes occurs with 'science working groups?' Your point that late planning and distributed management responsibilities drive up costs is very important, but do you intend to say that a large staff should be hired by the PI of the project as soon as the program gets the go-ahead?. . ."

DATA ISSUES AND COMPUTATION

Two reviewers commented on data archiving:

- "I found the report vague on the role of NSSDC and on its relation to archive centers. Will it merely provide a 'telephone directory?' Also, remote computer access, which will be here soon, seems to present potential problems which the report largely ignores. For example, once data in the archives is for a mission which is no longer active, where does the support for its distribution come from? How is its use "bookkept?. . ."

- "I think that data archiving is a task which, like the overall science operations, should be directed by scientists whose personal success depends on adequately archived data. . . Perhaps those who have had experience in retrospective studies would be candidates to manage this task. . ."

Other comments:

- "Twice in the report, the need for supercomputing was noted in passing. I think it is important to emphasize that supercomputing is no longer necessary only for large-scale theoretical problems (i.e., numerical simulations) but also is increasingly required for analysis of data. The data processing needs of several new missions in planetary studies as well as astronomy will require supercomputing. My impression is that there are no policies in most science disciplines making supercomputers available to users who need them. . ."

- "I think the only charge that was not well addressed was the section on Multispectral Observations. As the report says, this is a very complicated problem. Certainly the use of standardized data formats will help, but much more is needed. Since a 'solution' to the problem is not recommended, perhaps additional steps toward solving the problem could be recommended. At least one could make an attempt at identifying these investigations and initiating a problem-solving dialog with them. . ."

HUBBLE SPACE TELESCOPE AND STScI

Numbers of reviewers took the opportunity to reflect upon the cost of HST and the establishment of STScI, topics which have a long history and a tradition of strongly held views. One can offer only a sample of these comments here:

- "Although the report is correct in stating that the complexity of HST makes it quite different from other Astrophysics missions, I believe that the project does offer some lessons. (1) The report is certainly correct in emphasizing complex management as contributing to cost. Unfortunately, Astrophysics missions will continue to be plagued by the complications of the involvement of two or more centers, several PI's, and several other contractors. Each of these segments feels that it must do its job without 'interference.' In the case of the HST, the bad situation was exacerbated by the heated competition for STScI. . . (2) The PI's rebelled at providing data-handling software in a form which STScI could incorporate into its SDAS. Perhaps for future missions, this requirement should be announced in the AO. At the least, it should be included in the initial contract. (3) The development of SDAS was delayed and complicated by a 'scientific' rather than an 'operations' approach. . . (4) STScI chose to base their SDAS software on a transportable software system which was great in concept but not ready. The use of IRAF will probably prove to be sound, but the use of AIPS would have been less expensive. . ."

The letter continues with these observations:

"A problem that is not unique to HST, which makes it difficult to create smoothly working teams, is the strong caste system in the scientific community: first class--astronomers and physicists at university and quasi-university organizations (such as SAO); second class--Civil Servants; third class--support service contractors. As an example, STScI, with its emphasis on good scientists remaining scientists, does not give research time to the CSC scientists who support their operations, even though some of these are well recognized, publishing astronomers. . ."

Other reviewers commented as follows:

- "The only significant comment I would make concerns your stress on the technical complexities of HST. In particular, the report attributes cost differences between HST and HEAO-2, IUE, or IRAS primarily to larger numbers of management interfaces, more complex operations modes, and more intricate scheduling procedures. There are, in fact, relatively few of the HST science requirements that intrinsically demand particularly complex operating modes or scheduling constraints. Rather, it was the lack of attention to operability and the lack of 'user system engineering' across the complicated interfaces, especially early in the program, that contributed to the development of very complex systems. . ."

- ". . . Like most of the preceding long-lived missions identified earlier in the report, HST did have an organization which represented its users in place at an early point in the development program. This organization was the Science Working Group. . . In the cases of the other past astrophysics missions, similar SWG's played major roles in project scientific and cost tradeoff decisions. For some reason, this did not happen on HST. . . Several contributing factors seem likely. First, the fact that the HST Principal Investigators and science teams were supported by GSFC, and the HST Project Scientist and HST Observatory Development were supported by MSFC, may have made effective Project/SWG interactions more difficult. . . Second, the scientific discipline from which the HST PI's and their teams were drawn was not one which had traditionally worked in space or with NASA. They were, thus, probably unfamiliar both with the types of tradeoff decisions which are made during the formative stages of such a program and with the mechanisms employed by NASA to reach such decisions. Finally, the fact that an institute was planned, and was to have specific responsibility for looking after the interests of the user community, may have made the PI's less diligent about assuming this time-consuming role themselves. . ."

- "[I hope] that you will enlist the aid of the community outside NASA to exploit the new computer technologies and network concepts to gain the full advantages of independent institutional arrangements demonstrated by STScI at substantially lower cost. . ."

- ". . . What we should have bought [to manage HST] was a service company that was willing to implement software and operations tasks as a member of a cooperative, dedicated team, performing in a responsive and supporting role to the science/academic/research community. In fact, that is precisely how the IUE and IRAS programs proceeded, and I submit is a reason for the success of those programs that was recognized by your Study Group in labeling them as 'outstanding successes.' Another reason for the success of those programs is, I must state, the success of the hardware and software systems developers who, working as a team, provided a product that more than fulfilled requirements and expectations; that IUE, for example, could be reduced to a routine, highly productive research operations tool, was the result of the plans, designs, and methods invented by its founding fathers. . ."

AXAF AND SIRTF

Various reviewers offered perspectives on AXAF and SIRTF in the light of the report's conclusions and recommendations. Some of these have been incorporated into preceding sections.

Other comments:

- ". . . I was particularly glad to see AXAF compared to HEAO-2 and contrasted with HST, because I feel this is an important point to emphasize within NASA and throughout the astronomical community. . ."

- ". . . I hope that the [report's] conclusions will be heeded by NASA in implementing the AXAF and SIRTF missions. . ."

- "As you say, AXAF and SIRTF should not be compared in cost directly with HST, since this can be misleading. SIRTF hardware cost and complexity should be more like an upgraded IRAS rather than like HST, although the kind and quantity of raw data SIRTF produces may be similar to HST. But the SIRTF MO&DA program should be less complex than HST, because SIRTF will carry out longer observing programs for a smaller user community (SIRTF will probably receive hundreds, rather than thousands, of guest-observer proposals during each cycle). . ."

- "While I agree that HST is more complex than AXAF and SIRTF, I have the impression that you have underestimated the complexity of the instruments on the latter two missions. I will point out that each SIRTF instrument is estimated to cost about as much as one of HST's. . ."

- "[The] argument for the assertion that AXAF and SIRTF will be cheaper than HST hangs its hat on the technological issues involved, i.e., that the two missions are technologically simpler and therefore less risky. This appears to conflict with the report's primary conclusion that management issues, and not technological ones, drive mission success. . ."

- ". . . You point out that a variety of institutional settings can provide the 'core scientific expertise.' This is true, but there is a danger that this statement can become misconstrued that any one institutional setting is as good as another, so that centralization is OK. In diversity there is strength. You can't put all data centers at SAO or GSFC or anywhere else. You have to spread these around so that different approaches will be tried and a best approach eventually will be found that others emulate (willingly). . ."

SUMMARY (F. Martin)

The Director of the Astrophysics Division, NASA Headquarters, requested a study of operations and data handling for the era of the Great Observatories, with emphasis on AXAF and SIRTF. It was further requested that the general scientific community be involved in the study. The Study Group hopes that the approach and results of Phase I, II and III, as presented in this report, have satisfied this request.

The recommendations contained in Phase II speak for themselves, and the comments received as part of Phase III were generally supportive of these recommendations. Those that were not, or that raised specific issues or questions, reflected a deep concern and belief that the points raised were important, and that contrary views should not be ignored. While these comments are not all directly supportive, they do provide valuable insight, advice, and, in many cases, cautions.

Several points that emerged during the study deserve further comment:

For the most part, the recommendations of the report (which did involve participation from the Planetary program and JPL) are independant of the many astronomy disciplines. GRO will not be useful for planetary observations. AXAF will have limited utility for planetary studies (e.g., X-ray studies of Jupiter were conducted with HEAO-2). The SIRTF project is actively planning Solar System studies, and the highly publicized and discussed issues of planetary observations with HST are being resolved. As was pointed out in the comments contained in Phase III, planetary astronomers have made excellent use of past Astrophysics missions such as OAO, IUE and IRAS. The benefit of past Astrophysics missions to planetary research is clear, as is the benefit of planetary missions to astrophysics, with the future value of HST and SIRTF obvious to all. However, if this is to occur in a collegial environment, renewed efforts must be made at NASA Headquarters to ensure that all requirements are taken into consideration early in the program. The Directors of Astrophysics and Solar System Exploration should determine the best approach for resolving such conflicts and establish channels of communication that will help avoid unnecessary ones in the future.

Even though GRO is an important scientific element in the Great Observatory program, the limited number of γ-ray photons, the wide-field nature of γ-ray instrumentation, and the associated long observing times (weeks per source) make GRO a relatively straightforward mission from an operations and data-handling standpoint. Consequently, GRO was not given the same attention in this study as other efforts, since the lessons learned were relatively limited in their application to AXAF and SIRTF.

Despite the positive experiences cited in the report, there are still divergent views (pro and con) within the research community relative to the role of NASA centers and NASA scientists in the operation of Astrophysics missions. The process used to select the institutional settings for AXAF and SIRTF should ensure that these views, along with those of NASA scientists and Center management, are taken into consideration.

Communication and sharing of experience across Astrophysic projects is not always easy; there are four widely separated NASA centers involved, whereas most of the planetary flight projects are managed at JPL. Given the magnitude of the Astrophysics programs and the current stage of definition and development of various projects, consolidation may be difficult at best. Consequently, it is most important that every effort be made to ensure that the Astrophysics project teams develop a mechanism for sharing lessons learned.

Hardly any topic can stimulate as much heated discussion within NASA and the astronomical community as the management of HST, the role of STScI and what is and is not cost effective. It is clear that HST is unique among NASA projects and, in hindsight, many things might have been done differently. Obtaining agreement as to "what and why" may never be possible. In spite of different views, it is anticipated that HST will be an outstanding success. However, how we got there will in all likelihood be shrouded in the mythology that often characterizes major efforts.

As for basic management principles--"keep it simple"--the projects are complex enough without introducing unnecessary and untimely management interfaces. In addition, the importance of good data-handling practices is clear. The CODMAC recommendations provide an excellent road map for the future. Opportunities for AXAF and SIRTF lie ahead. Prompt attention should result in a program that is rewarding to both NASA and the scientific community. We hope that the present report will serve this end.

Appendix A

ATTENDANCE AT PHASE I WORKSHOP: 17-19 APRIL 1985

BLANCHARD, Paul	Applied Research Corporation
BLAZOSKY, Joe	Grumman Corporation
BOGGESS, Albert	Goddard Space Flight Center
CORRIGAN, Pat	Goddard Space Flight Center
COSTA, Richard	Goddard Space Flight Center
HALEM, Milton	Goddard Space Flight Center
HARRISON, Deborah	Applied Research Corporation
HAYNES, Norman	Jet Propulsion Laboratory
IMHOFF, Catherine	Computer Sciences Corporation
IRBY, Thomas	Marshall Space Flight Center
McCULLAR, Ronald	NASA Headquarters
MANNING, Larry	Ames Research Center
MARTIN, Franklin	Goddard Space Flight Center
MEAD, Jaylee	Goddard Space Flight Center
MILLET, Gary	Bendix Corporation
MYSLINSKI, Mike	Goddard Space Flight Center
NEWTON, George	NASA Headquarters
OPP, Albert	Goddard Space Flight Center
PASHBY, Paul	Goddard Space Flight Center
PEARL, John	Goddard Space Flight Center
PIEPER, George	Goddard Space Flight Center
RYAN, Thomas	Goddard Space Flight Center
SPENCER, Nelson	Goddard Space Flight Center
SQUIBB, Gael	Jet Propulsion Laboratory
TURNROSE, Barry	Computer Sciences Corporation
WEISSKOPF, Martin	Marshall Space Flight Center
WEST, Donald	Goddard Space Flight Center
WHITE, Ronald	Marshall Space Flight Center
WITTEBORN, Fred	Ames Research Center

- INCLUDES MISSION OPERATIONS SUPPORT CONTRACTORS

Appendix B

ATTENDANCE AT PHASE II WORKSHOP: 17-19 SEPTEMBER 1985

Workshop Participants

BERNSTEIN, Ralph	IBM Corporation
BLANCHARD, Paul	Applied Research Corporation
BOGGESS, Albert	Goddard Space Flight Center
BOYCE, Peter	American Astronomical Society
COSTA, Richard	Goddard Space Flight Center
GARMIRE, Gordon	Pennsylvania State University
GIACCONI, Riccardo	Space Telescope Science Institute
HARMS, Richard	Applied Research Corporation
HART, Richard	National Academy of Sciences
HARWIT, Martin	Cornell University
LINSKY, Jeffrey	Joint Institute for Laboratory Astrophysics, NBS/Colorado
MARTIN, Franklin	Goddard Space Flight Center
MEAD, Jaylee	Goddard Space Flight Center
OPP, Albert	Goddard Space Flight Center
SQUIBB, Gael	Jet Propulsion LaboratoryVANDEN
VANDEN BOUT, Paul	National Radio Astronomy Observatory
WEISS, Rainer	Massachusetts Institute of Technology
WEISSKOPF, Martin	Marshall Space Flight Center
WERNER, Michael	Ames Research Center
WITHBROE, George	Harvard-Smithsonian Center for Astrophysics

Presenters and Guests

BLACK, David	NASA Headquarters/Ames Research Center
EVANS, Nancy	Science Applications International Corporation
FROST, Kenneth	Goddard Space Flight Center
GREEN, James	Goddard Space Flight Center
HAYNES, Norman	Jet Propulsion Laboratory
IRBY, Thomas	Marshall Space Flight Center
JORDAN, Stuart	Goddard Space Flight Center
KNIFFEN, Donald	Goddard Space Flight Center
KONDO, Yoji	Goddard Space Flight Center
MANNING, Larry	Ames Research Center
McFADDEN, Lucy-Ann	University of Maryland
NEWTON, George	NASA Headquarters
PELLERIN, Charles	NASA Headquarters
RIEGEL, Kurt	National Science Foundation
TANANBAUM, Harvey	Harvard-Smithsonian Center for Astrophysics
WATSON, William	Goddard Space Flight Center
WEILER, Edward	NASA Headquarters

APPENDIX C

RELATED DOCUMENTS:

1. Institutional Arrangements for the Space Telescope (National Academy of Sciences, 1976) - The Hornig Report

2. Astronomy and Astrophysics for the 1980's, Volume I: Report of the Astronomy Survey Committee (National Academy Press, 1982) - The Field Report

3. Data Management and Computation, Volume I: Issues and Recommendations, Committee on Data Management and Computation, Space Science Board (National Academy Press, 1982) - The CODMAC Report

4. Solar-Terrestrial Data Access, Distribution, and Archiving, National Research Council, 1984

5. Trends in Planetary Data Analysis (NASA, 1983)

6. Planetary Data Systems Concept Document, Final Draft (NASA et al., 1985)

7. Space Research Data Management in the National Aeronautics and Space Administration, Draft Copy for Review Only (George Ludwig, 1985)

8. Astrophysical Data Requirements for Experiments on Space Station, Report of the ADRESS Working Group; First Draft, 1985

9. Telescience Operations and Systems Concepts for Command and Control of Space Station Payloads, A Preliminary White Paper (NASA, 1985)

10. In Defense of Institutes, by Riccardo Giacconi (Space Telescope Science Institute, 1985)

APPENDIX D

LIST OF ACRONYMS AND ABBREVIATIONS

ADRESS: Astrophysical Data Requirements for Experiments on Space Station
AE : Atmospheric Explorer
AIPS : Astronomical Image Processing System
AO : Announcement of Opportunity
ARC : Ames Research Center
AS&E : American Science & Engineering, Inc.
ATM : Apollo Telescope Mount
AURA : Association of Universities for Research in Astronomy
AXAF : Advanced X-Ray Astrophysics Facility
CSC : Computer Sciences Corporation
COBE : Cosmic Background Explorer
CODMAC: Committee on Data Management and Computation
CSAA : Committee on Space Astronomy and Astrophysics
DADS : Data Archive and Distribution System
DE : Dynamics Explorer
DRA : Data Reduction and Analysis
ESA : European Space Agency
FITS : Flexible Image Transport System
FY : Fiscal Year
GRO : Gamma Ray Observatory
GSFC : Goddard Space Flight Center
GSSS : Guide Star Selection System
HEAO : High Energy Astronomical Observatory
HST : Hubble Space Telescope
IPAC : Infrared Processing and Analysis Center
IRAF : Image Reduction and Analysis Facility
ISEE : International Sun-Earth Explorers
ISTP : International Solar Terrestrial Program
IUE : International Ultraviolet Explorer
JPL : Jet Propulsion Laboratory
KPNO : Kitt Peak National Observatory
MIT : Massachusetts Institute of Technology
MM II : Mariner Mark II spacecraft
MO&DA : Mission Operations and Data Analysis
MSFC : Marshall Space Flight Center
NAS : National Academy of Sciences
NASA : National Aeronautics and Space Administration
NBS : National Bureau of Standards
NRAO : National Radio Astronomy Observatory
NSF : National Science Foundation
NSSDC : National Space Science Data Center
OAO : Orbiting Astronomical Observatory
OSSA : Office of Space Science and Applications
PDS : Planetary Data System
PI : Principal Investigator
POCC : Payload Operations Control Center

R&D	:	Research and Development
SAO	:	Smithsonian Astrophysical Observatory
SDAS	:	Science Data Analysis Software
SEASAT	:	Sea Satellite
SIRTF	:	Space Infrared Telescope Facility
SMM	:	Solar Maximum Mission
SOC	:	Science Operations Center
SOGS	:	Science Operations Ground System
SOT	:	Solar Optical Telescope
STScI	:	Space Telescope Science Institute
SWG	:	Science Working Group
TDRSS	:	Tracking and Data Relay Satellite System
UARS	:	Upper Atmosphere Research Satellite
VLA	:	Very Large Array